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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 563

Low-Level and Nap-of-the-Earth (N.O.E.) Night Operations

(Opération de nuit à basse altitude et en rase mottes)

Papers presented at the Mission Systems Panel Symposium held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
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Theme

Tactical rotary wing aircraft and low-level, fixed wing aircraft operating in high threat areas require improvements in night and adverse weather conditions in order to increase survivability, improve operational performance, and to reduce pilot workload. Recent developments and the results of on-going programs suggest that increased automation and optimized integration of sensors, guidance/navigation, control and display systems, and weapons provide approaches to greatly enhanced capability in night operation. Operations/missions of concern include fire-support, attack, reconnaissance, and special operations.

For low-level and N.O.E. night operations, a core structure might include aided flight path control through generation and display of optional flight paths based on sensor data, terrain data bases on threat information; generation and fusion of sensor data for improved situational awareness and display of briefed and pop-up threats. Automated positioning, precision tracking, communications and mission planning, and data entry will also be available. Recent developments in integration of multi-spectral sensors, smart weapons, architectures, and processor and data distribution systems will permit different approaches to core structures.

The purpose of the symposium is to support the evolutions and development of alternative core structures which will lead to the fielding of effective low-level and N.O.E. night operations systems for fixed and rotary wing aircraft.

The following topics will be covered in the Symposium:

- Sensors
- Controls and Displays
- Automation and Processing
- Path Generation
- Weapons Integration
- Fault Tolerance and Safety
- Situational Assessment

Thème

Les aéronefs à voilure tournante tactiques et les aéronefs à voilure fixe à vol rasant évoluant en environnement à haut risque demandent certains perfectionnements pour le vol de nuit et par mauvais temps, afin d'accroître la capacité de survie, d'améliorer les performances opérationnelles et de réduire la charge de travail des équipages.

Certains développements récents, ainsi que les résultats obtenus par des programmes en cours laissent supposer que l'automatisation accrue et l'intégration optimisée des capteurs, des équipements de guidage/navigation, des systèmes de commande et de visualisation et des systèmes d'armes sont des facteurs clé qui permettront une grande amélioration de la capacité d'attaque de nuit. Les opérations/missions en question comprennent les tirs d'appui, l'attaque, la reconnaissance et les opérations spéciales.

En ce qui concerne les opérations à vol rasant et les opérations de nuit, les éléments essentiels seraient les aides au maintien de la trajectoire de vol par l'élaboration et la visualisation de trajectoire de vol par l'élaboration et la visualisation de trajectoires de vol alternatives basées sur des données capteur, des bases de données terrain contenant des informations menace, et l'élaboration et la diffusion d'informations sur des menaces briefées et ponctuelles. Le positionnement automatisé, la poursuite de précision, les télécommunications, la planification de la mission et la saisie des données sont aussi des éléments importants.

Les développements récents dans l'intégration des capteurs multispectre, des armes intelligentes, des architectures, des processeurs et des systèmes de diffusion de données doivent permettre d'autres approches du problèmes.

L'objet du symposium est de soutenir l'évolution et le développement de structures de base alternatives qui aboutiront à la mise à disposition de systèmes efficaces pour le vol à basse altitude et de nuit par des aéronefs à voilure tournante et à voilure fixe.

Les sujets suivants seront traités au cours du Symposium:

- capteurs
- commandes et visualisations
- automatisation et traitement
- élaboration de trajectoire
- intégration d'armes
- tolérance aux pannes et sécurité
- évaluation de la situation

Mission Systems Panel

Chairman:

Mr James RAMAGE
Chief, Flight Control
Flight Dynamics Directorate
WL/FIGS, Bldg 146
2210 Eighth St, Ste 11
WRIGHT-PATTERSON AFB
OH 45433-7521, USA

Technical Programme Committee

Chairmen:

Mr Paul B. HOMER
Head Attack Weapons Department
Code 35
Naval Air Warfare Center
CHINA LAKE, CA 93555-3500
USA

Dr John NIEMELA
Chief, Systems Technology Division
Command, Control & Systems
Integration Directorate
ATTN: AMSEL-RD-C2-TS
FORT MONMOUTH, NJ 077703-500
USA

Programme Committee Members

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Ing C. CESTRONE, IT
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IPA O. FOURURE, FR

Mission Systems Panel Executive

LtCol. P. FORTABAT, FAF

Mail from Europe:
AGARD-OTAN
7, rue Ancelle
France

Mail from US and Canada:
AGARD-NATO-MSP
Unit 21551 PSC 116
APO AE 09777

Tel: 33(1) 47 38 57 80
Telex: 610176 (France)
Telefax: 33(1) 47 38 57 99

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TECHNICAL EVALUATION REPORT ON THE MISSION SYSTEMS PANEL SYMPOSIUM ON LOW-LEVEL AND NAP-OF-THE-EARTH (N.O.E.) NIGHT OPERATIONS

Dr. Joseph A. Dasaro
U.S. Army Communications-Electronics Command
Command/Control & Systems Integration Directorate
Fort Monmouth, New Jersey 07703-5603, USA

1. INTRODUCTION

The Mission Systems Panel Symposium on Low-Level and Nap-of-the-Earth (N.O.E.) Night Operations was held at the Pratica di Mare, (Rome) Italy from 25 to 27 October 1994. The Program Co-Chairmen for this meeting were Mr. Paul B. Homer and Dr. John Niemela (both of the United States). The program, as presented at the symposium, is appended to this report.

Tactical rotary wing and low-level, fixed wing aircraft operating in high threat areas require improvements in night and adverse weather capabilities in order to increase survivability, improve operational performance, and reduce pilot workload. Recent developments and the results of on-going programs suggest that increased automation and optimized integration of sensors, guidance/navigation, control and display systems provide approaches to greatly enhance capability in night operation. Missions of concern include fire-support, attack, reconnaissance, troop insertion, and special operations. For low-level and N.O.E. night operations, a core structure might include aided flight path control through generation and display of optional flight paths based on sensor data, terrain data bases and threat information. Automated positioning, precision tracking, communications, mission planning, and data entry will also be available. Recent developments in integration of multi-spectral sensors, smart weapons, architectures, processors, and data distribution systems will enable expanded capabilities. The purpose of the symposium was to support the evolution and stimulate development of alternative techniques which will lead to the fielding of effective low-level and N.O.E. night operations systems for fixed and rotary wing aircraft.

Over the past twenty years a number of AGARD Symposiums sponsored by the predecessor Avionics and Guidance and Control Panels dealt directly or indirectly with the technology required to fly an aircraft at nap-of-the-earth or low level during night operations. Early efforts during the 1970's were primarily concerned with creating an image similar to the pilot's out the window view that could be used to control the aircraft. This image would be derived from visionic sensors such as image intensification or forward looking infra-red. Major investigations were undertaken to determine both the field of view and resolution required for a viable system. Display approaches fell into either the panel mounted or helmet mounted category with a number of symbology sets under consideration. Aircraft positioning and navigation subsystems were divided into three broad categories: inertial, doppler dead reckoning, and radio navigation aids. Extensive efforts were undertaken to combine these subsystems using statistical filtering algorithms. The crew then performed the pilotage function by integrating the combined position information with either paper maps or early map plotter displays to obtain geographic orientation, and then using the line-of-sight sensed obstacle and terrain information for the proper aircraft control inputs.

Recently, a number of efforts have been undertaken in the areas of sensors, controls and displays,

route planning, and flight path guidance, which when integrated, offer the potential to significantly improve the capability of an aircraft to perform missions at nap-of-the-earth or low level during night operations. The planners of this symposium felt that the time was opportune to focus on this important topic by reviewing technology and architectures that are emerging which could significantly enhance the alliance's capability in this operational area.

2. EVALUATION

2.1 Overview

The twenty papers presented at the symposium can be divided into the following nine (9) categories:

Operational Requirements
Simulation
Sensors (including sensor fusion)
Processing Architectures
Helmet Mounted Displays
Navigation and Positioning
Mission Planning
Communications
Flight Path Guidance

Each category was well represented by one or more papers and in many cases the information exchange in the topical area was strengthened by the discussions which took place at the end of each presentation. By the conclusion of the symposium it was clear that a definitive technical architecture has evolved to provide military aircraft with the capability to conduct night N.O.E. or low level operations. The operational requirements which drive this architecture were well stated in both the keynote address and paper 2. While there are some variants on this architecture and many issues to be addressed, there appeared to be a general consensus on this overall core architecture. A brief description of this core technical architecture will be used as the point of departure for this evaluation including references to the papers in the various categories and how they supported or extended the architectural concept.

2.2 Technical Architecture

The evolving technical architecture can be considered to consist of the following elements:

2.2.1 Data Bases

The mission starts with a planning function using available elevation and cultural data bases augmented with the latest threat data. A nominal route for the aircraft mission is determined and loaded into the aircraft processors. In general these data bases are of lower resolution than that required for night N.O.E. operations, therefore, an on-board sensor, such as a laser radar, must be used to augment the a priori obtained data base with high resolution near field information. This high resolution information must include data regarding wires and other obstacles in the flight path. In addition, the on-board data base must be continually updated with the latest threat data through both on-board sensors and through communication with battlefield command and control nodes. Papers 10 and 11 were excellent expositions of mission planning and tactical routing with paper 11 presenting performance data derived from flight testing. Paper 15 treated the topic of using data bases for derivation of flight functions such as terrain following. Paper 7 described a flight test of a system which derived and displayed flight path guidance by augmentation of an elevation data base with laser radar data. Key issues touched upon during the symposium involving this element of the evolving architecture included updating of this data base with the latest threat or intelligence data. Horizontal integration of the aircraft into the digital battlefield through exchange of position and route plans (or replans) with command and control nodes was also discussed. This information exchange involves the challenge of communications at low level, a topic which was addressed in papers 8 and 9.

2.2.2 Positioning/Navigation Systems

Positioning in the data base is generally achieved through a Global Positioning System (GPS) augmented by on-board systems such as terrain referenced, doppler, and inertial navigation subsystems. Accurate

registration of position in the data base is of paramount importance. Papers 7, 11, 12, and 24 dealt to varying extents with the navigation and positioning element.

2.2.3 Sensors
In addition to the visionic sensors which provide the pilot with an overall situation awareness of the immediate terrain, the obstacle and wire avoidance sensor becomes the key element of this architecture which allows flight at very low or N.O.E. altitudes. Papers 5, 17, 19, and 20 described different sensors (electromagnetic and laser) which are under development and test in the area of obstacle avoidance. Questions, answers, and discussions covered the issues of spectral regions and single versus multifunction capability. While there remains some work to be accomplished in each of these sensor approaches, it was clear that significant results are being achieved and this is one of the key technology areas that will allow the fielding of aircraft with enhanced low altitude night capability. Although there is early on-going work in the area of passive ranging for obstacle avoidance none of these efforts were presented at this symposium. Papers 4 and 6 presented concepts and programs in the area of sensor fusion and correlation for both enroute and targeting functions.

2.2.4 Displays
The display of choice for low altitude night operations has definitely settled on a helmet mounted display. Papers 22, 23, and 24 were an excellent exposition of the state-of-the-art in this element. Some issues still remain in the area of the optimum symbology for low-level, N.O.E. flight. This question is in general being addressed through simulations. Papers 21 and 22 addressed the simulation area in a comprehensive manner.

2.2.5 Flight Path Guidance
The term flight path guidance is used here to describe the unifying element for the future low-level, N.O.E. night systems. Early work in this area was primarily concerned with giving the pilot spatially correlated situation awareness by means of a display of the outside world. To aid in the pilotage task symbology was overlaid on the display. The new technologies of data bases, route planning, precision positioning, obstacle and wire sensors, and displays, have been integrated by algorithms that provide precise flight path guidance to the crew. This path guidance takes into account beyond line of sight considerations through the exploitation of the available data bases and route planning (and replanning) capabilities. This data could be integrated and coupled to an automatic flight control system to provide hands-off flight capability at low altitudes. Papers 7, 11, 13, and 15 dealt with these system level issues. Paper 14 dealt with the area of system processing fault tolerance appropriate for such flight critical functions.

2.3 Operational Architecture
The operational architecture in which a low-level, N.O.E. night capability would be fully exploited was covered in the keynote address by Brigadier General Thomas J. Konitzer of the U.S. Army. General Konitzer started with a detailed description (including video tape) of Task Force Normandy - a south west Asia operation in which eleven helicopters (8 Apache, 2 Pave Lows, and 1 Black Hawk) conducted a night low level attack on Iraqi air defense installations. General Konitzer then went on to describe the operational requirements of the future, ending with the need for horizontal integration of the aviation elements into the digitized battlefield. Paper 2 (Night Attack) by Colonel C. Dortomb of France then presented the rationale for night operations and the requirements for functions such as mission planning, navigation/positioning, and targeting. Both of these presentations gave the symposium an excellent operational context in which the evolving technology and architecture could be presented.

3. CONCLUSION

The operational requirements which initiated alliance efforts in developing aircraft systems with low-level and N.O.E. night capability are as valid today as twenty years ago when many of the national and multinational efforts were initiated. This symposium provided an excellent assessment of where the alliance is today with regard to development of the technology to meet the military need. An overall systems architecture has evolved with variants and issues in a number of the elements. Of significance is the emerging capability of dynamic real time algorithms which provide accurate flight path guidance at the altitudes under consideration using advanced sensor technology integrated with battlefield data bases. In all areas this symposium met the goals of the program committee. The command and control aspects of aircraft operations at low altitudes provide a number of operational and technical challenges which must be addressed, especially for future allied operations. These considerations were beyond the scope of this symposium, but would be a worthwhile topic for a future symposium.

L'ATTAQUE DE NUIT

Colonel Claude DORTOMB
Bureau des systèmes d'armes
Etat-major de l'Armée de l'air
24, Bd Victor
00460 ARMEES
France

RESUME

La capacité d'effectuer des frappes nocturnes est recherchée par tous les pays. Compte-tenu des contraintes budgétaires actuelles et des capacités des capteurs optroniques, ceux-ci représentent aujourd'hui la réponse la mieux adaptée à ce besoin.Du système le plus simple au plus compliqué, allant des jumelles de vision nocturne aux nacelles de désignation Infra-rouge, ces systèmes valorisent pour un coût raisonnable les avions en service.

LISTE DES ABREVIATIONS

ATLIS	Automatique Traking Laser Illuminator System
FLIR	Forward Looking Infra-Red
GPS	Global Positioning System
IR	Infra-Rouge
JVN(# NVG)	Jumelles de Vision Nocturne
PDL-CT	Pod de Désignation Laser à Camera Thermique.

1 INTRODUCTION

Depuis ces dernières années un grand nombre d'intervention des forces aériennes ont eu lieu sur des théâtres d'opérations pour lesquels elles n'étaient pas particulièrement préparées.

L'évolution du contexte géostratégique entraîne une diversification des conditions d'emploi de l'aviation de combat qui n'avait jusqu'alors pas été envisagée. Ainsi des opérations de rétorsion, de rétablissement de la souveraineté d'un pays ami ou de maintien de la paix ont mis à jour des besoins sinon nouveaux du moins, dont les priorités ont changé. Des exemples sont dans nos mémoires, ou encore d'actualité. De l'opération Desert Storm, aux opérations en Bosnie, il est apparu que les forces aériennes devaient mettre en oeuvre les systèmes d'armes les plus sophistiqués pour acquérir et maintenir une supériorité sur l'adversaire, seule capable d'éviter les pertes. L'augmentation de l'efficacité par l'utilisation de technologies de pointe n'est cependant pas à la portée des budgets actuels de la défense, dans de nombreux pays. Il importe donc de trouver le meilleur compromis entre l'efficacité par la capacité d'effectuer des frappes puissantes et précises, sans restriction de lieu ni de temps, et les ressources budgétaires qui peuvent y être consacrées.

Dans l'état actuel, les technologies optroniques qui offrent la capacité de prononcer des attaques de nuit représentent, pour de nombreux théâtres d'opérations, la meilleure réponse à ce besoin.

2 LES BESOINS OPERATIONNELS

Contrairement aux mauvaises conditions météorologiques, la nuit n'est pas un phénomène aléatoire.Il est donc particulièrement important de pouvoir poursuivre les opérations la nuit. Une étude statistique montre qu'en hiver en Europe centrale la nuit claire représente plus de 12 heures par jour ; comparativement les mauvaises conditions météorologiques représentent environ 7 heures.

Pour effectuer des frappes précises et puissantes, avec un minimum de pertes, et une très grande probabilité de réussite, il convient d'obtenir la cohérence entre les différents moyens utilisés pour conduire une attaque, et de mettre en difficulté les défenses.

L'attaque de nuit permet d'assurer la permanence de la menace aérienne et contraint l'adversaire à disposer d'un système de défense très évolué. Sur de nombreux théâtres d'opérations, la nuit apporte une certaine invulnérabilité du fait de l'emploi de conduite de tirs optiques.

2.1 Reconnaissance et identification

L'attaque d'un objectif terrestre par un vecteur avion nécessite une connaissance préalable de celui-ci. C'est encore plus vrai la nuit que le jour.

Les moyens de reconnaissance utilisés devront permettre une analyse de la nature de l'objectif afin de déterminer les armes appropriées à sa destruction et préparer le capteur utilisé au moment de son identification avant le tir.

Les technologies optroniques répondent à ces besoins.

2.2 Conduite de tir

Pour obtenir l'efficacité recherchée, la conduite de tir doit permettre la désignation précise du point visé à distance de sécurité et les calculs de temps de largage des munitions. Le guidage des munitions vers l'objectif est indispensable pour obtenir la précision recherchée.

Les technologies optroniques répondent également à ces impératifs.

2.3 La navigation et l'environnement

La navigation de nuit peut faire appel aux mêmes technologies que le vol tout temps. Cependant si l'on utilise un système d'armes ne disposant pas d'un radar de suivi de terrain, les capteurs optroniques peuvent apporter une réponse adaptée au besoin de vol très basse altitude de nuit temps clair.Il importe cependant de fournir au pilote une aide à la navigation dans le plan vertical, la précision de navigation dans le plan horizontal étant supposée de base

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

(Centrale inertielle couplée GPS et/ou recalée par corrélation d'altitude).
Les capteurs optroniques apportent une aide précieuse mais ont des performances étroitement liées aux conditions d'environnement : éclairement stellaire, contraste thermique, hygrométrie,etc...

2.4 Préparation de mission

La réalisation d'une attaque de nuit nécessite une préparation minutieuse et un choix adapté des points de recalage ou des points initiaux.
La connaissance des conditions d'environnement devra permettre ce choix.

3 LES MOYENS DISPONIBLES

Pour répondre aux besoins opérationnels, les capteurs optroniques constituent une réponse adaptée, cohérente et économiquement accessible. Différents degrés de sophistication peuvent être retenus.

Si on recherche une frappe de très grande précision (écart métrique), dans l'état actuel, seules les technologies optroniques répondent à ce besoin. Elles nécessitent cependant un minimum de visibilité.

Les mêmes technologies utilisées pour le recueil de renseignement, l'identification, le recalage ou le tir peuvent être séparées en deux grands types :

- l'amplification de lumière, utilisant la bande visible ou le très proche infra-rouge;

- les capteurs infra-rouge

Le premier type est utilisé par les jumelles de vision nocturne (JVN).Celles ci utilisent des tubes de 3° génération amplifiant la lumière (lunaire ou stellaire) dans la bande 0,55µm à 0,95µm. Le champ instantané est de 40°, mais étant porté par le pilote tout le champ de vision de la cabine de pilotage est accessible. Cependant la portée d'identification des objectifs est relativement limitée, et les objectifs ou les points de recalage doivent être de grosses tailles et de préférence à développement vertical. Elles ont pour avantage essentiel leur faible coût comparativement aux autres équipements. Cependant leur utilisation impose un traitement particulier de l'éclairage cabine et des instruments, afin de ne pas se situer dans la bande spectrale des jumelles et de faire ainsi chuter de façon très importante les performances.
Le second type comprend tous les capteurs utilisant les deux fenêtres de transmission Infra-rouge : 3-5 µm ou 8-12 µm.
Dans l'état actuel les équipements en service utilisent le plus souvent la bande 8-12 µm. De nombreux développements sont en cours pour utiliser la bande 3-5 µm.
Deux types principaux d'équipement doivent être distingués :

- les FLIR (Forward Looking Infra Red) grand champ, fixe ou orientable. L'armée de l'air va mettre en service le FLIR RUBIS sur MIRAGE F1CR.
- les nacelles de désignation, de reconnaissance, de poursuite et de tir, petit champ. L'armée de l'air dispose du PDL -CT sur MIRAGE 2000D.

Certaines nacelles permettent les deux fonctions avec des performances moins bonnes. En effet comme pour la lumière visible, la performance d'un système IR est étroitement liée à l'ouverture de la pupille et au champ.

4 L'ATTAQUE DE NUIT

Une mission d'attaque de nuit nécessite :

- une préparation de mission très complète
- une navigation précise comportant des recalages

- l'identification et la désignation de l'objectif ou d'un point initial

- le tir et la poursuite éventuelle.

4.1 La préparation de mission

Le chargement des données dans les systèmes d'armes modernes s'effectue au travers d'un module de chargement, de diverses technologies, lui-même chargé par un système sol de préparation de mission.

Ce système doit permettre à l'équipage d'effectuer les meilleurs choix d'attaque de l'objectif en fonction de sa nature, de sa situation géographique (masques éventuels) et des défenses connues. De nuit il est de plus nécessaire selon la nature du système optronique utilisé d'avoir une connaissance de la météorologie plus précise (éclairage lunaire ou non, couverture nuageuse) ainsi que l'hygrométrie et la température (performances IR en 8-12 µm ou en 3-5 µm). Le contraste thermique de l'objectif devra être également estimé pour pouvoir prévoir la distance d'acquisition.

4.2 La navigation

La navigation de nuit temps clair ne nécessite pas de systèmes aussi sophistiqués que la pénétration tout temps. Les systèmes optroniques permettent d'effectuer la navigation à vue très basse altitude. Toutefois les défauts de ces systèmes (champ trop faible, profondeur de champ) entraînent pour le pilote une mauvaise perception du relief et des défilements, du fait du manque de vision périphérique
Le FLIR provoque ce qu'on appelle un "effet tunnel", qu'il est indispensable de compenser avec des JVN.
Le manque de perception du relief nécessite une aide à la navigation dans le plan vertical : ficelle de vol automatique, ou vol sur fichier terrain.
La précision de navigation dans le plan horizontal est implicite en mission d'attaque de nuit.
Le recalage de la navigation inertielle pourra faire appel au GPS.

Cependant la disponibilité de celui-ci ne pouvant être garantie en tout lieu, et à tout moment, le système d'armes devra disposer d'un moyen de recalage autonome : à vue à l'aide des moyens optroniques utilisés pour l'attaque ou par corrélation d'altitude. Selon la nature et le choix du point de recalage il sera possible d'utiliser les JVN, le FLIR ou le PDL-CT.

4.3 Identification et désignation

Cette partie du vol représente la charge de travail la plus importante pour l'équipage. Si le problème peut comporter certaines similitudes avec la désignation d'un point de recalage, la différence essentielle est que cette phase , très courte et qui ne peut être reportée, conditionne la réussite de la mission et se déroule dans un environnement hostile.

L'utilisation de la nuit permet une certaine invulnérabilité vis à vis des conduites de tir peu sophistiquées, mais complique aussi la tâche de l'équipage.

Des variations très importantes des distances d'acquisition d'un même objectif peuvent être constatées selon l'hygométrie et le contraste thermique, et donc l'heure de l'attaque.

Cette contrainte pourra amener l'équipage à un tir à plus courte distance que celle qui était escomptée à la préparation de mission et à se retrouver ainsi confronté aux défenses à très courte portée.

4.4 Tir et poursuite

Selon le système utilisé et le mode de tir, il s'agira le plus souvent d'autoriser le largage des munitions et de maintenir des ordres de pilotage issus du calcul qui a été initié par la désignation.

Cette phase pourra paraître longue à l'équipage confronté aux défenses . Il faudra de plus dans le cas d'un tir à distance de sécurité avec une nacelle de désignation laser s'assurer du maintien de l'illumination sur l'objectif (poursuite automatique non perturbée par les masques ou fumées).

C'est pourquoi la désignation et l'illumination par un autre avion ou par un illuminateur au sol présentent un très grand intérêt opérationnel.

L'équipement récent de l'avion Jaguar avec un détecteur de tache laser ELIAS ouvre cette capacité "tir et oubli". Avec un armement à guidage terminal, le coup au but devient possible de nuit avec une conduite de tir relativement simple.

5 LES AMELIORATIONS SOUHAITABLES

Les limitations qui ont été énoncées montrent la voie à suivre pour améliorer ces équipements :

- augmenter le champ et la distance d'acquisition.
Pour les théâtres d'opérations où l'hygrométrie est plus forte, l'utilisation de la bande IR 3-5 µm semble de nature à améliorer les distances d'acquisition.

- intégrer les JVN au casque du pilote sans augmenter notablement le poids. Pour permettre les vols prolongés et l'éjection sans perte de qualité par rapport aux tubes actuels.

- prendre en compte la menace d'éblouissement laser.

6 CONCLUSION

Les théâtres d'opérations auxquels les forces aériennes de l'OTAN ont été confrontées depuis quelques années ont démontré tout l'intérêt des technologies optroniques.

De nombreux théâtres ne comportent pas de défenses très évoluées, cependant de jour à basse altitude, le risque missile IR courte portée est latent.

L'attaque de nuit maintient la permanence de la menace aérienne, et apporte une certaine invulnérabilité.

Ainsi l'utilisation de systèmes d'armes simples valorisés par des équipements optroniques devient possible, et permet de faire l'économie des technologies radar.

Ce constat ne doit pas être considéré comme une situation acquise et immuable. Le développement des contre-mesures (menace laser) et des conduites de tir du missile sol-air montrent qu'après avoir mis l'accent sur la réduction de la signature électromagnétique des avions de combat il sera impératif de réduire leur signature IR. De plus les progrès envisageables de l'imagerie radar avec les radars millimétriques doivent permettre d'envisager la fusion des images optroniques et radar afin de "durcir" les capacités d'attaque toutes conditions et en particulier de nuit.

AN APPROACH TO SENSOR DATA FUSION FOR FLYING AND LANDING AID PURPOSE

G. Balzarotti, L. Fiori, B. Midollini, G. Viglialoro

FIAR S.p.A.
Via G.B. Grassi, 93 -20157 Milano - Italia

SUMMARY

Modern aircrafts, operating in hostile environments, at night and in adverse weather conditions, are usually equipped with a number of sensors, both active and passive, which separately provide the pilot with data and images and represent a substantial aid during the mission.
Novel techniques are currently under development to further improve the effectiveness of the mission by integrating and interpreting the produced data before making them available to the pilot.

This paper analyses the data fusion following a growing integration level criteria. The levels in the integration flow where the fusion is effectively applicable are investigated starting from raw signal (lowest level) up to processed data from sensors, even located on different sites (highest level).
Schematically the integration levels considered in the paper will be the following:

Sensor/pre-processing
processing
display
operative modes
multiple platforms

At the first level, data fusion simply takes place on raw signals, or on pre-processed signals.
Processing Level involves sets of data suitably processed within each sensor.
Display level data fusion aims at the optimum presentation of multiple sensors information to the operator. The fourth level is relevant to the management of different sensors for the achievement of the best effectiveness for the specific operational mode.
Finally, data fusion is considered within a structured scenario where sensors even located on different platforms (aircraft and on ground) can share the data.

1. INTRODUCTION

The design of sensor data fusion requires at first an accurate *definition* and *identification* of the total information available. In fact in modern avionics, an enormous amount of data from the aircraft itself or from sensors located on ground or on other aircraft can be used, after an appropriate analysis.

We will start this task from the very general scheme of Figure 1. The words resources-system-requirements of figure a. are substituted with more appropriate definition for our specific application in the figure b. The system has been named as *Image and Data System for Navigation*. The basic requirement has been identified in providing a *reliable and safe aid for flying and landing*. The *resources* are the complete set of measurements of the variables associated with the events occurring in the world.

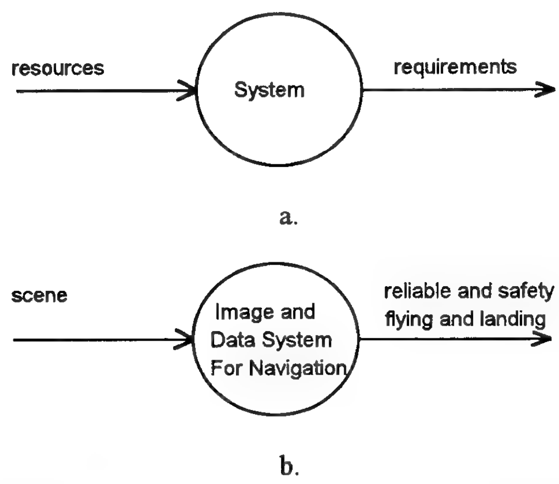

Figure 1. The problem of data fusion is approached in scheme a. by starting in defining the general *input* and *output* for the system. In the specific case the basic requirement has been identified in providing reliable and safe flying and landing operational modes (scheme b.).

In defining the data provided by sensors, a possible system engineering approach is to

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suppose that sensors can work properly, limited only by physical constraints. In that case the *data* that the Data Fusion Engineer will deal with will contain the whole information that the class of sensors can provide. The *data* will contain the information of sensor observation on the events occurring in the world, subject to the "theoretical" sensor's measurement errors.

In the real case, volume, weight, installation, technical and cost constraints force us to deviate from the above assumption. Therefore the measurement errors in the actual case will be worse than the theoretical ones and some measurements can also be completely missed.

The output data are displayed to the pilot via cockpit instrumentation, Head Up and Head Down Displays or Helmet Mounted Display. In this paper we will not enter the question about the characteristics of the best support for reporting information. However the availability of a suitable means to display picture in raster mode and symbols is considered essential, at least to present images from the IR sensors. The preference, under the point of view of our analysis, is for Helmet Mounted Displays, which are more flexible in operation.

2. THE INTEGRATION LEVELS

The general scheme of Figure 1 is to be developed to highlight all the possible sources of data useful for navigation. In Figure 2 the system is detailed using the physical location of the sensors as discriminating parameter.

Ownship platform includes all the sensors located in the aircraft e.g. altimeter, radar, FLIR, obstacle warning system, INS.

With ground platforms we refer to all the sensors located on the ground, specifically to allow flying and landing e.g. runway marker.

Finally, with airborne platforms we refer to all the sensors located in the A/C linked with our platform and dedicated to support the navigation of our A/C.

The Sensed Data Management is responsible for the effective use and fusing of the data from the different sources.

The Sensed Data Management function is further detailed in Figure 3. Data are subject to two different processing then the fusion is performed, including also stored maps and mission data.

An important point in the analysis of the information for data fusion is to distinguish the *fertile* data from the *redundant* data. This is particularly important in data fusion devoted to navigation.

We will call *fertile* the information which has a real content of innovation or, equivalently, which is a measure of the reality. Two sensors could provide fertile information measuring the same reality. One of those would be redundant for the system.

The fertile data will bring information useful to increase the situation awareness. The redundant data allow to improve the reliability of the system and the safety of flight. The two sets should be well balanced: an high level of redundancy could be positive for the reliability but it is also an indication that we try to perform fusion of data that have too much similarity or, that the sensors are located in inappropriate sites. In this case the amount of work necessary to fuse data could not be justified by the result, due to the weakness of the information.

The comparison between the sets of the theoretical data provided by sensors as limited by physical constraints only and the actual data is an useful test if either system or sensors are to be redefined. If fusion design on ideal sensors outputs weaknesses information, then the architecture of the system must be probably reviewed.

To avoid error in defining redundancy, we think that exchange of data between sensors must be only performed by the unit that has the task to control data fusion. To clarify this point let us consider the example of the horizon indication provided in the video of a sensor which receives the altimeter data from the aircraft bus. Some questions arise. Is the horizon reconstructed on the basis of the altimeter data or is it provided by data properly grabbed by the sensor itself ?

In the very likely case where the information is generated by using both, which is the *weight* of the two sources in generating the output data? Does this weight change with operational conditions? In this case it is the sensor itself to perform data fusion. This process is out of control of the fusion engineers and an answer to the above questions can unlikely be provided by the sensor supplier too.

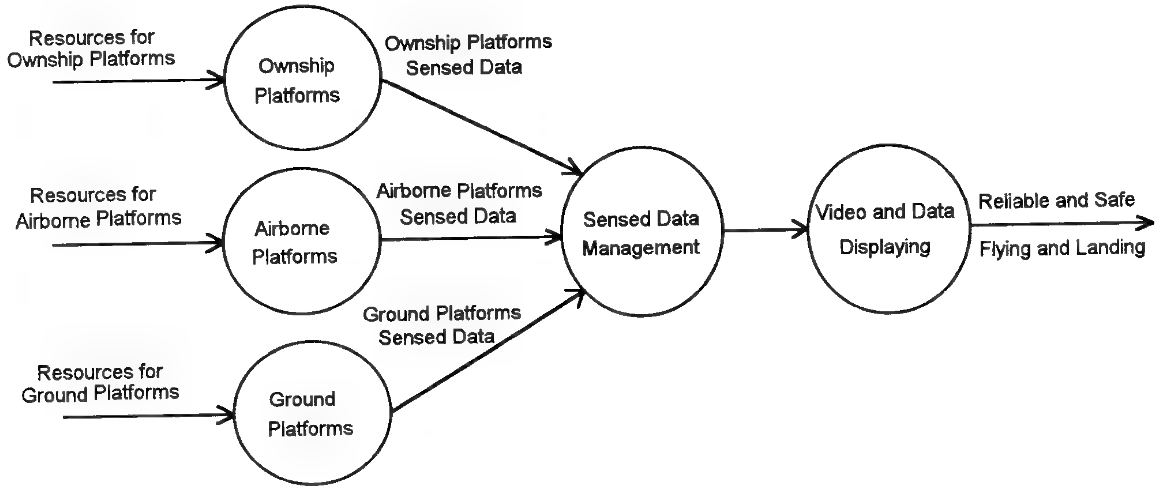
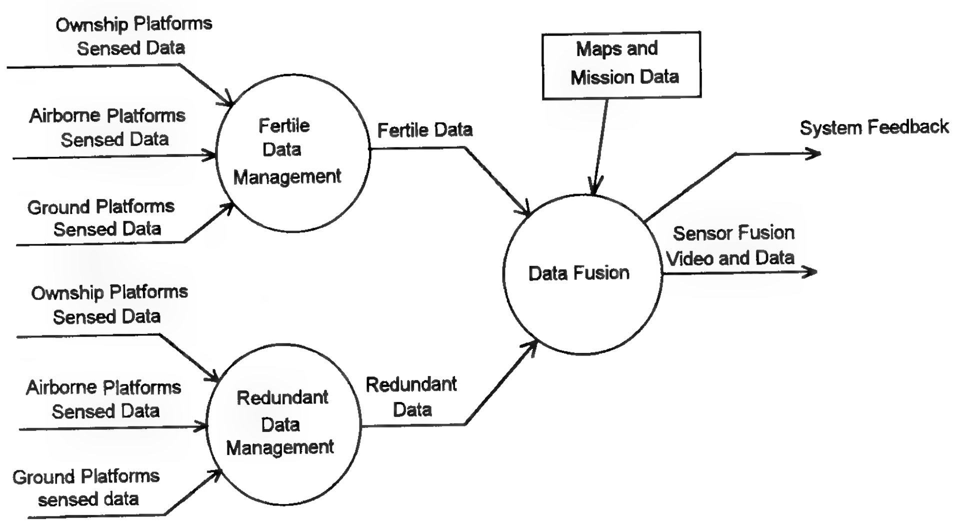


Image and Data System for Navigation

Figure 2. The Sensed Data from the possible sensors dedicated to navigation and located in different places are managed to provide a reliable and safe flying and landing operational mode.



Sensed Data Management

Figure 3. The data from sensors are processed to provide the system with a consistent information. The identification of *fertile* information is essential to allow an effective fusion. An appropriate management of redundant data is essential in flying and landing to maximise the reliability and the safety.
The system feedback signal is generated in this phase. Exchange of data at early stage (directly between sensors) can create a non determinable condition in terms of *fertile* and *redundant* data.

The horizon information provided by this sensor cannot be reasonably used for any further profitable data fusion, neither to increase the reliability due to the inherent ambiguity of data.

The criticism in defining the fertile and redundant information is that the content of innovation could change during operation. If two sensors provide equivalent measurement of the real world in a nominal condition, they could have a very diffent behaviour in a particular environmental condition. The redundancy could therefore disappear in many cases.
In Figure 3 the sensor feedback signal has the purpose to exchange data between sensors. As it has been mentioned the signal has to be managed with specific attention. We will not further enter the merit of this question in the paper and the signal is highlighted in this diagram only.

Figure 4 provides details on the Ownship Platform. We assume a similar configuration for the other platforms. All the platforms are supposed to be in communication with the Sensed Data Management.

We have included in the task of the Sensed Data Management the decision to send data directly the pilot's attention without passing through any fusion processing. For example this is the case of the infrared picture on HUD and the altimeter data on the cockpit instrumentation. The pilot will perform in this case his own *data fusion*.

Figure 5 details the IR Sensor and Radar. In the breakdown we have highlighted three different stages where the data can be grabbed for the fusion:

pre-processing
processing
and
video processor.

The wider content of fertile information is in the pre-processing data. From the scheme of Figure 5 it is evident that the input from the real world is obtained at Sensor/Pre-processing level. The stages which follow in the processing path work on the information available at that level. The content of the output Video & Data will be therefore equivalent or, more likely, smaller than the one available at the first stage of the process. Note that, within the definition used in this document, the data available at the output of video processor are not redundant with respect to the data at the output of the sensor/pre-processing stage, as are generated by the same source.

The data processor could modify the content of information by using internal data file (e.g. maps). This, however, does not increase the amount of *fertile* information, even if it could be so considered from the pilot point of view. Maps and mission data are pre-stored data and they are not a measure of the events occurring in the real world. We think that for an appropriate analysis, the stored data are to be considered at *data fusion level* (see Figure 2). There is however no loss of consistency of the method if they are suitably located in the relative sensor.

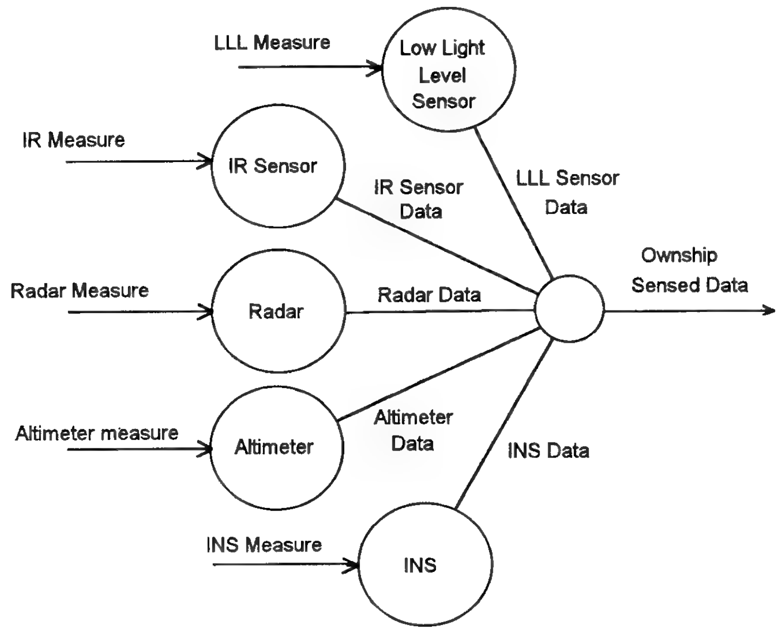
The obvious advantage in using more mature data is to have available, at higher level, data *ready to use,* thus avoiding to ask the Sensed Data Manager to operate with too much rough data . The fusion of rough data requires, in addition, an accurate knowledge of the sensors architecture and characteristics.
The decision of the *cooking level* of data is a very important point for Data Fusion System Engineer. We are actually devoting time in this direction.

As the decision for the whole system cannot be easily approached by a general point of view, we are limiting the studies to a few sensors. However, interesting results can be reached also through a less general approach.

The *interpretation*[1] of the sensory information should directly follow the *definition* of the information available that has been outlined in this section.
The *interpretation* and the development of tools to perform coherently is one of the main aim of research in Sensor Fusion. We have avoided to enter this argument but we will go on the *a priori* approach to perform data fusion by following an *integration level* criteria.

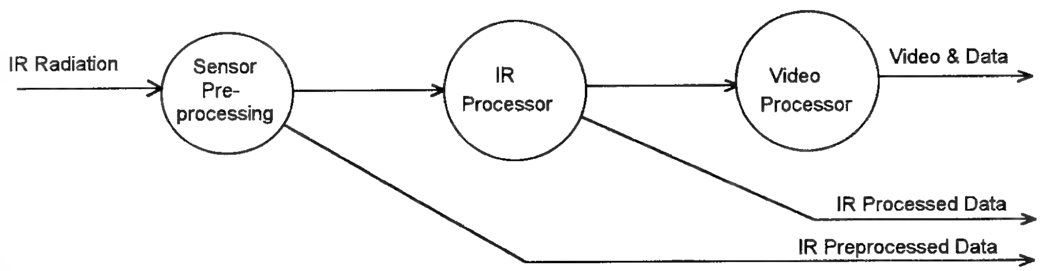
The Sensed Data Manager could in principle operate in order to build up the final output by using all data available in spite of the level of processing. A simplified approach used in this paper consists in limiting the fusion at equal level of integration, following the level structure outlined in this section, that is:

sensor/pre-processing
processing
display
operative modes
multiple platforms.

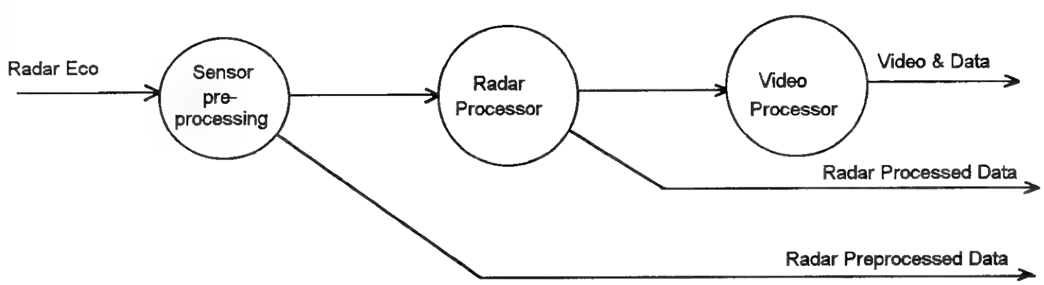


Ownship Platform

Figure 4. A wide number of sensors located on the A/C provide information of the events occurring in the world. The figure highlights some of them. The complete control of the information requires that no data can go directly from one sensor to the other one without the supervision of the fusion management.



IR Sensor



Radar

Figure 5. The data fusion can be performed by using the *well cooked* data available on the output of the sensor (Video & Data) but the use of intermediate data is of paramount importance for the data fusion system engineer to optimise and maximise the use of the information grabbed by the sensors. The figure highlights two possible intermediate points were data can be picked up for fusion.

The information will be analysed at any level separately and the Sensed Data Manager will not perform a further fusion of the data processed at each single level.

Note again that Sensed Data Manager does not generate any new *fertile* information, but it builds and organises the sensed data in a more effective and readable way. This is very likely obvious, but we would like to highlight to prevent misinterpretation of the word *fertile*.

3. THE FUSION

We can now analyse the fusion, following the different levels of integration mentioned above. This approach will allow us to identify the various areas of applicability for data fusion.

For radars and infrared sensors, we are currently interested in data fusion at display level, together with sensor/pre-processing level, as already anticipated. Our activities have a general character, but a particular emphasis is being paid to aspects related to navigation aid.

The study of fusion levels can lead, as a consequence, also to the need for a re-definition of the communication system. As an example, data fusion at sensor/pre-processing level could very likely imply the necessity to increase the communication rate of the aircraft buses. On the other hand, the use of multiple platforms has to take into account the communication availability and its reliability.

As far as radar and infrared sensor data fusion is concerned, we think to solve the problem of communication implementing a common data processor for the two sensors. In this way, the impact on the aircraft would be limited to the links between apparatus, without affecting the global communication system, which is sometimes rigid or completely exploited.

3.1 Sensor/Pre-processing Level

This is very likely the most interesting and promising data fusion level. It is also, for sure, the one which has been actually less utilised, even if it has been subject to wide studies.
Fusion at this level makes use of raw data, in order to recover the widest part of fertile information, also by implementing local processing which is not usually performed. The analysis at pre-processing level allows to direct the equipment design towards the data fusion concept.
In this case the sensor will be created for data fusion.

In the sensor/pre-processing level the outstanding aspect which we have to face is that the information provided by the radar and by the infrared sensor are fertile and are different, but somehow too much different.

The radar is able to evaluate the range accurately but is weaker in evaluating angle when compared with an infrared sensor which, on the contrary, cannot directly measure ranges.
This could be compared to the case of pieces from different construction kits, which cannot match together. The only possibility could be to build up two different constructions and place them side by side. The design of sensors should be addressed to remove this event and to obtain homogeneous information.

Roughly speaking, the approach that we are using consists in breaking down the information supplied by a sensor until we find a subset which is comparable with the information supplied by the other sensor. Then, the comparison and fusion[2] are performed at subsets level and the signal finally is reconstructed starting from the new subsets.
In fusing two imaging sensors with different spatial resolution, as an example, a low-pass filtering of the image with higher resolution is performed, until a resolution equivalent to the one of the second sensor is obtained. Then the two images are fused together and the resulting low resolution image is once again fused with the original high resolution one. In the case of an IR sensor and a millimetric radar for obstacle avoidance, the contribution from the two sensor might lead to an image absolutely not homogeneous in the 3 spatial directions, but with a high degree of information. The most suitable way to present the information is then examined according to the characteristics of the display and following ergonomic factors.

The break-down is not limited to the spatial domain, but has to be performed also in the signal intensity and the spatial and temporal frequencies domains.

3.2 Processing Level

This is the classical level for data fusion. The data from Radar and IR Sensor are made available at A/C bus and the Data Fusion Engineers can design the fusion by interpreting and processing the data on the basis of the statistic and characteristics of these data. The problem connected with the homogeneity[3] just highlighted is still present, but few changes can still be reasonably operated on the source of the data at this level of integration.

3.3 Display Level

This one is very likely the most immediate data fusion level. In the past it has been relatively ignored with the trend towards presenting the pilot with as much data as possible. The obvious result was an information often confusing and thus useless.
The display presentation technique is practically a stand alone science now and it is an argument of specialised study performed by the military research centre (i.e. by the final users). It is not however generally considered as a branch of the data fusion.

As the output of the data fusion cannot be independent from the method to present it, in our approach the analysis of how to present data is an integrating factor in reaching the reliability and safety requirements for flying and landing aid (Figures 1 and 2).

Simply speaking, the studies of data fusion dedicated to an aircraft provided with an Helmet Mounted Display for pictures and symbols presentation is necessarily different from those for an aircraft provided with HUD only. This is specifically true for navigation systems where the method to display data plays a basic role in the safety of the flight itself. At this level the data fusion *shall manage the displaying of the available data.*

We are basing the evaluation of the picture quality on the operative characteristics of the system rather than on the pure evaluation of the spatial resolution and the signal to noise ratio.
The picture is required to be effective for the specific application it is devoted to, therefore, for navigation, a picture with enhanced edges could be much more effective than a picture with a wide range of grey levels. In evaluating the performance of the system, an approach based on the techniques of Received Operating Characteristic[4] (ROC), i.e. based on statistic techniques which take into account the observer's decision criterion, is therefore more appropriate than techniques based on the perceptual sensitivity, as the well known Signal Detection Theory (SDT), which involves basically the MTF and the noise level. The differences in the consistency of the performance prediction is very significant especially in evaluating if the picture is comfortable for the operator.

3.4 Operative Modes Level

The Data Fusion Management System, being based on operability indications from the different sensors and on flight data, is able to identify the best parameters from sensors, or to select one sensor instead of another. Changing the parameters or the sensor utilised might be considered as a true change in the operative mode; i.e. on the basis of the flight/environmental conditions, the fusion system at this level *selects (or advises as the preferred one) the information to be utilised.*

The fusion at Operational Mode Level requires the use of knowledge based techniques and fuzzy logic. The decision criteria, if the information provided by a sensor is or not jet acceptable, cannot be in fact determined by conditions on applicability range.

3.5 Multiple Platforms Level

The use of multiple platforms brings for sure notable benefits to navigation. This is certainly the most safe and reliable method, especially for landing, used in airport all over the world.

Particularly in this case we have to face the problem of the data *weight and validity* to approach the data fusion. How it is possible to profitably fuse data provided by a high precision or highly reliable system with sensors of limited performance? In landing with ground-based radar aid and in presence of fog an infrared sensor could bring only a very limited benefit. The information would not be redundant, since the two sensors are in different locations, and in this case fusion would take place at the previously described operative modes level. The Data Fusion Manager, after flying with the IR sensor aid and approaching landing, should switch to ground-based aided

landing (i.e. should indicate such necessity to the pilot).

An important factor, which should be however kept into account is the pilot's familiarity with the system.
Probably, even if from the point of view of fertile integration the IR sensor would bring a very little contribution, the availability of the IR image of the external world, even if degraded, could increase the pilot's confidence and awareness. In this case a profitable fusion could be obtained, even if not easily measurable occurrences.

4. CONCLUSION

The activities we are performing in the field of data fusion are based on an approach which takes into consideration the wide frame of global system design, thus allowing the possibility of verifying the consistency of the results.

Practical implementation, in fact, should constantly compare to requirements and this, particularly for navigation, cannot be profitably performed and suitably managed at sensor level only.

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MULTISPECTRAL IMAGE CORRELATION FOR AIR-TO-GROUND TARGETING

W. R. Ditzler, M. J. Boyd, T. J. Corcoran, M. S. Franklin,
J. E. McKnight, H. C. Ottenhoff, R. W. Tyhurst, and M. M. Wirtz

Targeting Systems Integration Section

Naval Air Warfare Center/Weapons Division
China Lake, CA 93555-6001
United States

1. MOTIVATION

A primary cause of failure in tactical air-to-ground missions is that the aircrew fails to find the assigned target. This is the case even for missions against *preassigned, large, stationary* targets, such as bridges, supply depots, and air-defense sites, for which reconnaissance and satellite images of the target and its surroundings are available for the mission planning process.

An important reason for this poor performance is the limited time available for target acquisition, especially when target defenses necessitate low-level ingress. During the time a target is visible to aircraft sensors, the aircraft is also visible to the target's defense systems. The time required for air-to-ground targeting with present systems (for example, to lock a targeting FLIR onto an aimpoint) is comparable to the response time of air defense systems. Clearly, minimizing the time needed to find and recognize targets is crucial for making attack missions more survivable.

Survivability is enhanced if the attack mission can be carried out without the need to "pop up" to use a targeting sensor. In a typical low-level attack mission, 8-10 sec is available for the targeting process, from appearance of the target to weapon release. However, a pilot cannot remove his attention from flying the aircraft for this length of time, especially at night using night-vision systems. Pilots who have tested night vision systems for low-level flight estimate that 1.5 to 2 sec is the maximum allowable time to concentrate on a head-down display under these conditions.

A near-term solution to the targeting problem must let the human operator make the final decision. The system described in this paper automates the search for the target (or an offset aimpoint) by sending video from one or more of the aircraft sensors to an image correlator. The correlator finds the best match to an image of the target area, supplied from mission-planning data, and displays the resulting target position overlaid on the sensor image. The aircrew is required to look at a head-down display only long enough to confirm or deny the correlator's result. The correlator can then automate the process of locking an imaging missile seeker onto the target.

2. TECHNICAL APPROACH: OVERVIEW

Land-attack Multisensor Correlation (LMC) is a subtask of the Air-Launched Weaponry Block program, sponsored by the Office of Naval Research and performed by the Infrared Systems Branch (code C2153) of the Targeting and Fire Control Division of the Naval Air Warfare Center/Weapons Division. Its six-year program, which began in FY 1988, is nearing completion. It was planned as a successor to the Fighter/Attack Avionics Targeting Demonstration (F/AATD), which in 1983-1987 carried out a successful demonstration of multisensor/multitarget tracking for air-to-air targeting.[1] Like F/AATD, it is a "6.2-level" demonstration program: no longer basic research, but not yet focused on applying technology to a specific weapon system or platform.

Experience gained in F/AATD resulted in a set of strong convictions about the best way to develop targeting technology. First and most important, real sensor data should be used as inputs as soon as possible in the life of the project. Real sensors always have idiosyncracies not predicted by simulation; and, especially for imaging sensors, it is easier to get real data than to create (or buy) a simulation with adequate realism. Second, the system should consist of off-the-shelf commercial components (both hardware and software) wherever they provide adequate performance. Finally, the basic concept should be simple and straightforward.

The challenge for LMC was to come as close as possible to a demonstration under operational conditions, within a limited budget and schedule. It was decided that the best approximation to a system installed in a testbed aircraft was a real-time image-processing system in the laboratory, with inputs provided by replaying actual aircraft sensor and avionics data. The VME (Versabus Motorola Eurocard) backplane architecture was selected for the best combination of flexibility, affordability, and computing power. It also provides a path of minimum resistance for transition to an operational system, because militarized and ruggedized processor boards are commercially available.

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LMC was structured as a two-phase program. In Phase I (1988-91), the basic sensor-invariant correlation algorithm was coded and tested on general-purpose computers, and a real-time image-processing system to house it was designed and integrated. In Phase II (1991-94), a significantly more powerful image processor was designed to house an upgraded set of algorithms. The Phase II system consists entirely of flyable modules, to enable an in-flight demonstration with the same hardware in a planned follow-on program.

3. ALGORITHM DEVELOPMENT

Before the structure of the real-time system could be finalized, the image-processing algorithms which it houses had to be selected. During the first year of the LMC program, a survey of possible techniques for image correlation was carried out.

The direct approach of intensity correlation was ruled out immediately, because intensities generally do not match in data from different sensors. At the opposite extreme of sophistication, techniques of object recognition from the field of computer vision were examined. This technology is not mature enough for a near-term application, and at present requires too much computing power for use in real time.

It was decided that the best approach is to extract *sensor-invariant* information from the images to be correlated, specifically the *shapes* of objects. The most straightforward method is *edge detection*. Several textbook approaches to edge detection were coded, in order to evaluate performance on sample sensor images. This technique is much simpler than the "model-based" approach to multisensor correlation, which depends on classification of scene elements in one sensor image to predict their signatures as viewed by other sensors.

The overall structure of the correlation process is diagrammed in Figure 1. On the left are the steps for transforming a reference image of the target area into a sensor-invariant "template." This portion of the correlation process was originally envisioned to take place as part of the pre-mission planning process, using a mission-planning workstation containing digitized overhead imagery of the theater of operations. However, the recent emphasis on attacking time-critical mobile targets implies that template-making should also be housed in real-time reconnaissance assets, such as the J-STARS aircraft, with the results datalinked to the weapon platforms.

The first step in template generation is edge extraction. Standard edge-extraction algorithms, as described by Nevatia and Babu,[2] for example, consist of three steps. First, a spatial gradient operator finds regions of non-uniform intensity. Next, gaps in potential edges are bridged. Finally, the edges are thinned to one-pixel-wide lines. The LMC algorithm differs only slightly from this "standard" technique. The size of the convolution matrix (gradient operator) is matched to the resolution of the sensor, in order to reduce the effects of detector gain fluctuations and noise. The F/A-18 targeting FLIR is oversampled, so that edges cannot be less than 3 pixels wide; 5 x 5 and 7 x 7 Sobel-type matrices give good results. The standard 3 x 3 Sobel operator works well with satellite images. F/A-18 ground-map radar images require preprocessing to suppress speckle; a 5 x 5 median filter is adequate.

The connectivity and thinning operations are combined into a single step. A sparse search finds potential edges. The search for horizontal edges is carried out along well-spaced vertical lines; for vertical edges, along well-spaced horizontal lines. Once a pixel with edge strength above a starting threshold is found, a search along the direction of the potential edge begins. Each pixel on the crest of the "ridge" of edge strength is added to the edge. The search bridges short gaps where the edge strength on the ridge falls below a minimum tracing threshold. The sparse search makes it necessary to have a safeguard so that the edge-tracing procedure does not find the same line multiple times, on different sweeps (or, worse, follow a closed loop *ad infinitum*). After an edge has been traced, its pixels are "blanked out" to make sure the edge is not found again.

This sparse-search algorithm requires about an order of magnitude less throughput for the linking and thinning steps than the standard "textbook" approach, with no loss of performance. The convolution step is the major computational burden; however, parallel processors well matched to this task are readily available.

The edges found by the tracing procedure are not stored in an image-plane format, but as ordered lists of pixels, compressing the amount of data which must be transferred to the weapon platform by orders of magnitude. Additional compression results from fitting straight line segments to as much of each edge as possible, and eliminating pixels between the endpoints of straight segments. The result typically consists of several thousand bytes of data, compatible with transmission over low-bandwidth datalinks.

After compression, elevation data is added to each point in the template. This step is essential because the reference images are not taken from the same point of view as the aircraft sensors, so they must be transformed to the correct perspective. This step requires three-dimensional data. LMC has used the Digital Terrain Elevation Database, registered with its "mission planning" images, to assign vertical coordinates to large-scale terrain features. Data from the French SPOT satellite (10 x 10 meter pixel size) is used to emulate mission planning imagery without the need to handle classified data.

All of the software modules required for template creation have been integrated into a "user-friendly"

package housed in a Sun workstation. All operator interaction takes place with mouse commands in a graphics window. The operator begins with a large-scale image of the China Lake region (60 km square), "zooms in" on the region of interest, and selects the aimpoint. The automatically generated template can be edited to delete unwanted lines which are unlikely to be sensor-invariant (for example, paint stripes on runways and shadow edges). The entire program consists of 2000 lines of **c**. In addition to making templates, the program can generate synthetic perspective images from any point of view, by "draping" the satellite image over the elevation data.

The right side of Figure 1 shows the steps involved in correlating the template with sensor video on the attack aircraft. First, the template is converted to the perspective of the selected aircraft sensor, based on information on the sensor gimbal angles, aircraft orientation, and estimated slant range to the target, read from the avionics bus. The perspective transformation must be performed in real time on the attack aircraft, in order to allow deviations from the preplanned flight path. After the points in the template list have been converted to sensor image-plane coordinates, pixel positions must be interpoated between the endpoints of each straight-line segment in the template. The Bresenham algorithm,[3] which is one of the most efficient interpolation methods known, is employed.

An important realization in developing the real-time correlation system was that only one of the images to be correlated must go through the full edge-extraction process. Finding the best match between two images can be performed by converting one image (the "template") to a set of lines, then tracing these lines over the Sobel convolution of the other image. The best alignment is where the line integral is maximized. This technique takes several orders of magnitude less computation than a full image-to-image correlation, because of the sparse set of pixels in the template. With a special processor optimized for tracing line integrals (the "correlation module" to be described in a later section), several hundred template positions can be tested in each 33 msec video frame.

Even this video processing rate is not adequate to test all possible template positions in each frame, so an efficient search technique must be used to acquire the target. We use a "pushbroom" or "trip wire" algorithm. Given the aircraft's current altitude and orientation, perspective-transformed templates are generated with a fixed distance from the target to the aircraft, but different offsets perpendicular to the flight path (see Figure 2). The target is located by searching for a peak in correlator output as a function of time and template lateral offset, during the interval when the target is expected to pass through the sensor field of view.

After a correlation peak has been detected, the system transitions from search mode to track mode and follows the template across the sensor's field of view. The tracking process is complicated by the time lag required to generate a set of templates with a new perspective transform, and transfer them between processors (over 1 sec with the current system architecture). When a tentative match is made between a video frame and a template position, the acquisition process begins by generating a set of templates with centers arranged in a rectangular array, or "track box." The track box is centered on the image-plane position to which the best-match template would move during the time needed to generate the template set (based on extrapolated aircraft INS data), as diagrammed in Figure 3. Meanwhile, correlation with the original set of "pushbroom" search templates is continued, in case the match is a false alarm and the track cannot be sustained--a simple "multiple hypothesis" approach.

4. REAL-TIME SYSTEM ARCHITECTURE

The VMEbus Template Matching System (VTMS) is the real-time image-processing system designed to house the correlation algorithms. In Phase I of the LMC program, an in-lab demonstration configuration was integrated and tested. In Phase II, the system has been redesigned so that all modules can be housed in a ruggedized VME chassis for in-the-air testing.

As diagrammed in Figure 4, the VTMS consists of VMEbus compatible cards performing eight tasks:

1. System control
2. 1553bus/VMEbus interface
3. Template perspective transformation
4. Digitization of input video
5. Image edge enhancement
6. Video-to-template correlation
7. Monitoring correlation scores
8. Digital-to-analog conversion for graphics output

When the Phase I system was designed, off-the-shelf modules were available to perform all of these functions except the video-to-template correlation itself. The processor for this step, which will be described in the next section, was designed and built at NAWC-WPNS. The VME backplane itself is not used for real-time transmission of digitized images, because of throughput limitations. Dedicated MAXbus ribbon cables provide high-speed pathways directly from one module to another. The entire system is synchronized and controlled by signals on the backplane.

A Motorola 68040 single-board computer (SBC) controls system timing and data transfers, and also monitors the scores calculated by the correlation module to determine the peak position. A second 68040 is dedicated to the task of template perspective transformation. Software for these processors is edited and assembled on a Sun **SPARCstation 370**, then downloaded to the SBC via a serial port. Debugging

of the code takes place on the SBC with a local debugger in ROM. Algorithm development and testing also takes place on the Sun system. A key decision in designing the Phase II system was to minimize the task of integrating multiple VME processors by using the framework of a commercial real-time operating system, the **VxWorks** system and development environment. All system software is now written in **c**, rather than assembly language. Calls to standard system routines are used for transfer of data and commands from module to module.

The 1553bus Monitor is a single-board module which stores 1553bus messages for access by the SBC. The aircraft flight parameters in these messages determine the perspective of the 2-dimensional templates to be downloaded to the correlation module. For the in-lab demonstration, 1553bus messages and sensor video, recorded simultaneously in flight, are synchronized in replay by hardware based on an IBM-compatible PC.

The laboratory system uses RS-170 video as input. Since F/A-18 FLIR and radar video is in RS-343 format, it is scan-converted, then written to laserdisc for maximum convenience of playback in the lab. All of the actual video-processing components of the system can accept RS-343 input, which will be necessary for in-flight operation with current sensors.

All of the standard image-processing functions of the Phase II system are performed by a single **MaxVideo 20** module. These include digitization of the input sensor video, two 7 x 7 matrix convolutions for the horizontal and vertical components of the edge-strength vector, and combining the two components to provide the magnitude of the vector as output. In addition, an internal buffer is used to save the best correlated video frame for static display. The MaxVideo also performs graphical overlays and digital-to-analog conversion for diagnostic output, which include a real-time histogram of the correlation scores and superimposing the best-match template on either the raw or the edge-enhanced sensor video. In the Phase I system, these operations required six individual modules.

5. THE CORRELATION MODULE

The Phase I real-time video/template correlation module was built on a single 9U jumbo wirewrap card. In order to be flyable in a testbed aircraft, the Phase II correlation module was built on three 6U wirewrap cards, functionally separated into image memory, template memory, and accumulator cards.

Edge-enhanced images enter through a MAXbus interface in a 10MHz pixel stream. Two 1-megabyte frame buffers store the image alternately, in "ping-pong" fashion. Correlation takes place with data in one buffer while the other is being loaded. Similarly, two memory arrays are provided to contain the set of templates to be matched; one array can be reloaded while the other is being used.

The basic concept of correlator operation is diagrammed in Figure 5. During the template matching operation, the template memory array is addressed by a counter. Each output from the template memory array is an address for the image memory array. In this fashion, each template location of each template extracts the corresponding pixel value from the stored image. The pixel values read from the image memory array are summed in a 20 bit digital accumulator. When the last point of each template is reached, the accumulator score is written into a first-in-first-out (FIFO) memory for access by the 68040 SBC which sorts the scores.

The key to real-time operation of the correlator is rapid access time for the template and image memories. The fastest memories available with adequate size have 30 nsec access time. This speed allows the correlator to test 300 templates per video frame, assuming an average template size of 1500 pixels.

Although no off-the-shelf processing module was available four years ago that could perform the correlation algorithm in real time, processor technology has improved. In preparation for follow-on efforts, our group is investigating the feasibility of replacing the custom correlation module with several off-the-shelf signal-processing boards containing TMS320C40 processor chips. The change would give the system capability to perform image-processing operations unrelated to template matching, without additional hardware. Use of one or more TMS320C40 processors for the template perspective transform will also reduce the transformation time lag to acceptable levels.

6. PERFORMANCE ANALYSIS

In the initial years of the LMC effort, sensor video collected for other programs was used as system input for algorithm development. In order to make quantitative measurements of system performance, however, it was necessary to obtain flight data planned aaround the LMC concept. With the cooperation of the F/A-18 Weapons System Support Activity at NAWC-WPNS, two 90-minute data-collection flights were carried out in late 1993. Aircraft position, measured by the China Lake range instrumentation, was recorded.. On board the aircraft, time-tagged sensor video (either targeting FLIR or ground-map radar) and selected 1553bus messages were recorded.

Four standard targets were selected to test the correlator. SPOT images of the targets, and the templates created from them, are shown in Figure 6 and 7. The two flights yielded a total of 32 targeting passes with the FLIR, and 7 passes with the radar. The target remained in the sensor field of view for an average of 2000 video frames (65 sec) per pass. All passes were at medium to high altitude, 3000 to 4000

meters. The FLIR was operated in wide-field-of-view mode, with a typical slant angle of 15°.

The analysis presented here concentrates on the FLIR data. However, successful correlation of the templates with the ground-map radar images has also been demonstrated. For analysis purposes, the template-matching algorithms were housed in a Sun workstation, and flight data was replayed considerably slower than real time. The main reason for this change is that the "pushbroom" search mode was very unfamiliar to the pilots of the data-collection flights; as a result, most of the target passes were in stabilized ground track mode (*i.e.* pointed approximately at the target position). To initiate template tracking, the image plane had to be searched both horizontally and vertically, which the real-time system is not yet configured to do.

To obtain a position fix with a passive forward-looking sensor like the FLIR, it is necessary to know either the slant range or the relative altitude between aircraft and target. This information also determines the scale factor of the templates in the sensor image plane, reducing the number of dimensions of the search process. Successful target acquisition and tracking were demonstrated using the barometric altitude of the aircraft, but its known uncertainty would dominate the performance analysis. Therefore, a high-precision slant-range measurement, such as a laser rangefinder would provide, was simulated by using the range instrumentation data on aircraft altitude.

Figures 8 and 9 show the crossrange and downrange position errors for 8-second segments of two passes against the "sewage ponds" target, comparing position fix from the image correlator with range instumentation. Tracking was initiated at the first frame of the sequence. The noticeable "banding" in the downrange errors--the tendency for points to lie on a set of lines sloping downward to the right--results from the quantization of position in the FLIR image plane. The spacing between bands is the width of one raster line. The error values can be entirely accounted for by combining two known error sources: the accuracy of the range instrumentation and the drift in the aircraft INS system, used to calculate sensor pointing direction.

Figure 10 presents the results of a different approach to performance analysis. Persistent problems were encountered in determining precise range coordinates for several of the test targets, so a relative measurement of template-matching performance was adopted. Identifiable "point-like" objects, such as navigation beacons at the airfields, were used as the aimpoints for the templates. The position of these objects was manually measured in a sampled set of video frames from eight targeting passes, two for each of the four test targets. This "true" position of the aimpoint in the image plane was compared with the aimpoint position determined by the correlator.

The plot is a 2-dimensional histogram of downrange and crossrange errors for 360 individual video frames. The x and y axes are scaled in units of pixels in the FLIR image plane. For the geometry of these flight tests, one FLIR pixel subtends approximately 4 meters on the ground in the crossrange direction. The standard deviation of the points is 2.7 pixels crossrange and 2.8 pixels downrange. Mean value of the error is 0.1 pixel crossrange and 1.4 pixels downrange. 90 per cent of the points are within 5 pixels of the origin. We conclude that the accuracy of the correlator's aimpoint determination is consistent with the pixel size of the SPOT reference image, which dominates the error budget for these flight tests.

7. CONCLUSIONS

The Land-attack Multisensor Correlation program has demonstrated the feasibility of multispectral image correlation to perform reliable automated targeting at near video frame rates. Accuracy of the aimpoint determination is determined by the resolution of the reference image and the targeting sensors. Current rules of engagement require that a human operator must decide on the validity of the target assignment before any weapon can be launched. Therefore, the limiting speed factor beecomes the response time of the human operator, who must confirm or reject the aimpoint provided by the system. Design of the operator interface is thus a critical issue, and research on the most efficient way to present sensor data for comparison with the reference image is needed..

In 1992-93, high-resolution synthetic-aperture radar (SAR) imagery of the Chinal Lake area was collected for this program by several SAR testbed aircraft. Templates generated from the SAR data have been successfully correlated to both FLIR and low-resolution ground-map radar images. This approach has the potential to provide a real-time targeting capability for attacking movable targets When the movable targets are located by a real-time surveillance system, templates of the target vicinity can be transmitted *via* low-bandwidth datalink to already airborne strike aircraft.

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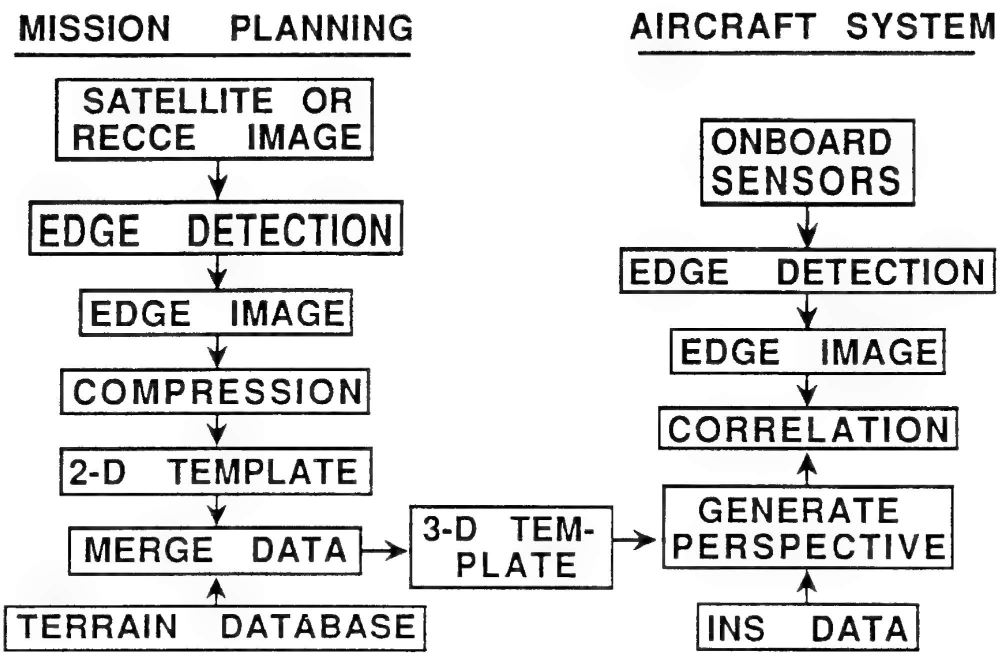

FIGURE 1. STRUCTURE OF THE LMC TEMPLATE-MATCHING PROCESS.

- TEMPLATE SPACING MATCHES SIZE OF CONVOLUTION MATRIX
- EACH TEMPLATE HAS ITS OWN PERSPECTIVE RECONSTRUCTION
- CORRELATOR SCORE PEAKS AS FUNCTION OF TIME AND TRANSVERSE POSITION WHEN THE LINE OF TEMPLATES PASSES OVER THE TARGET

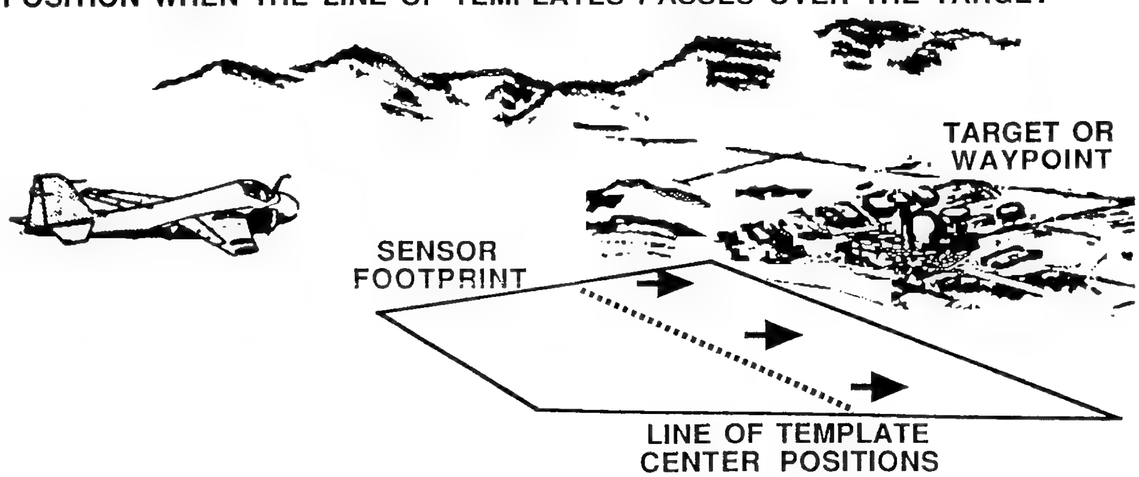

FIGURE 2. THE "PUSHBROOM" SEARCH PATTERN.

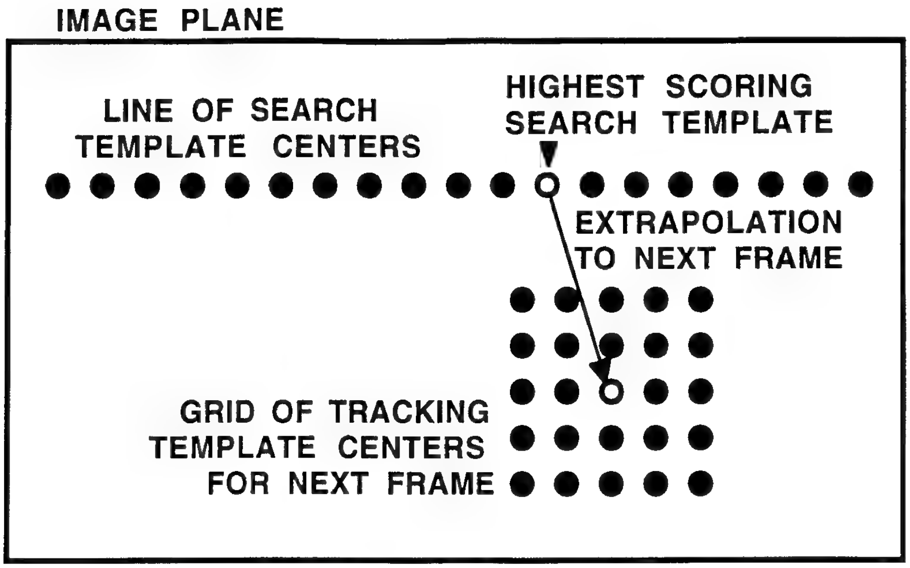

FIGURE 3. TRANSITION FROM SEARCH MODE TO TRACKING MODE

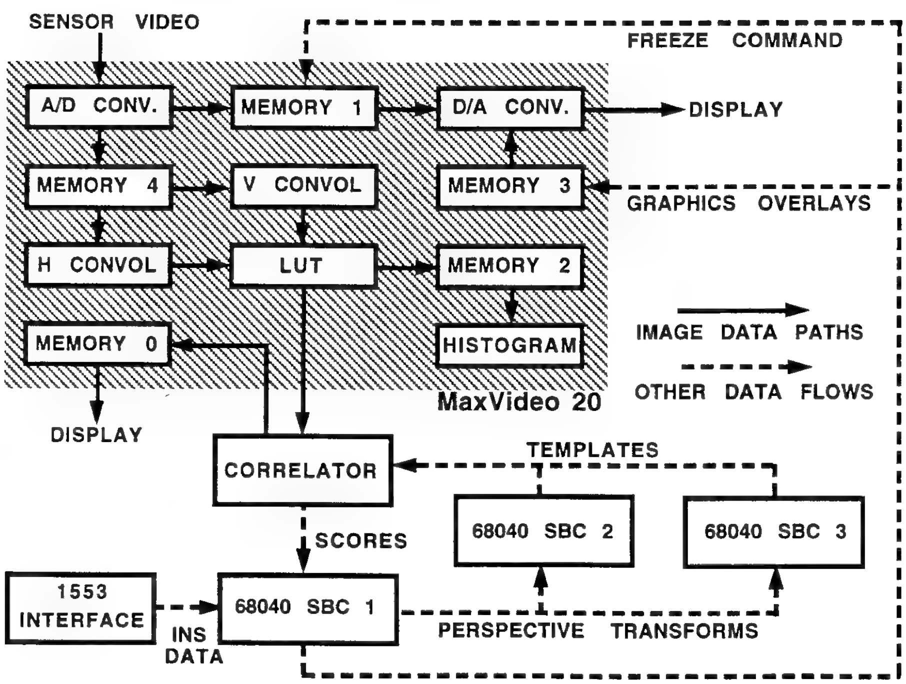

FIGURE 4. HARDWARE ARCHITECTURE OF THE PHASE II REAL-TIME SYSTEM

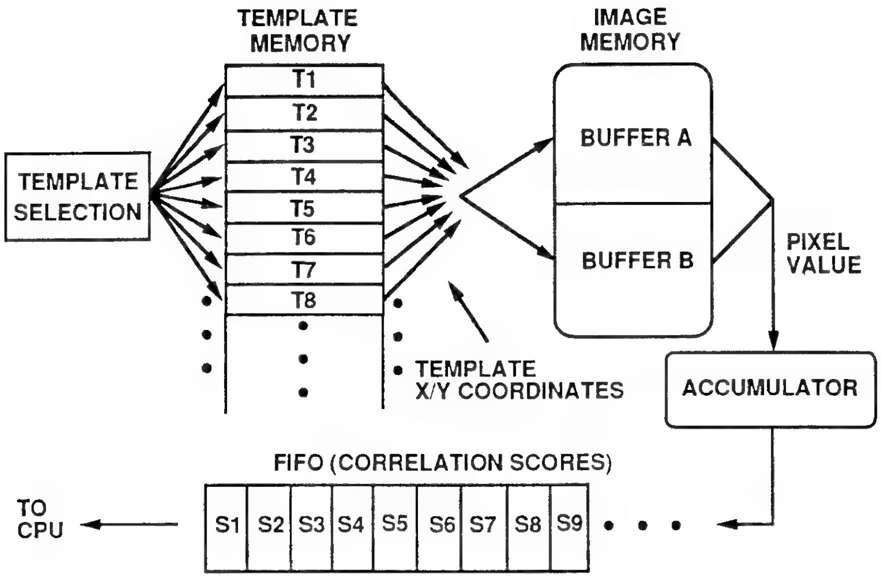

FIGURE 5. BASIC STRUCTURE OF THE CORRELATION MODULE

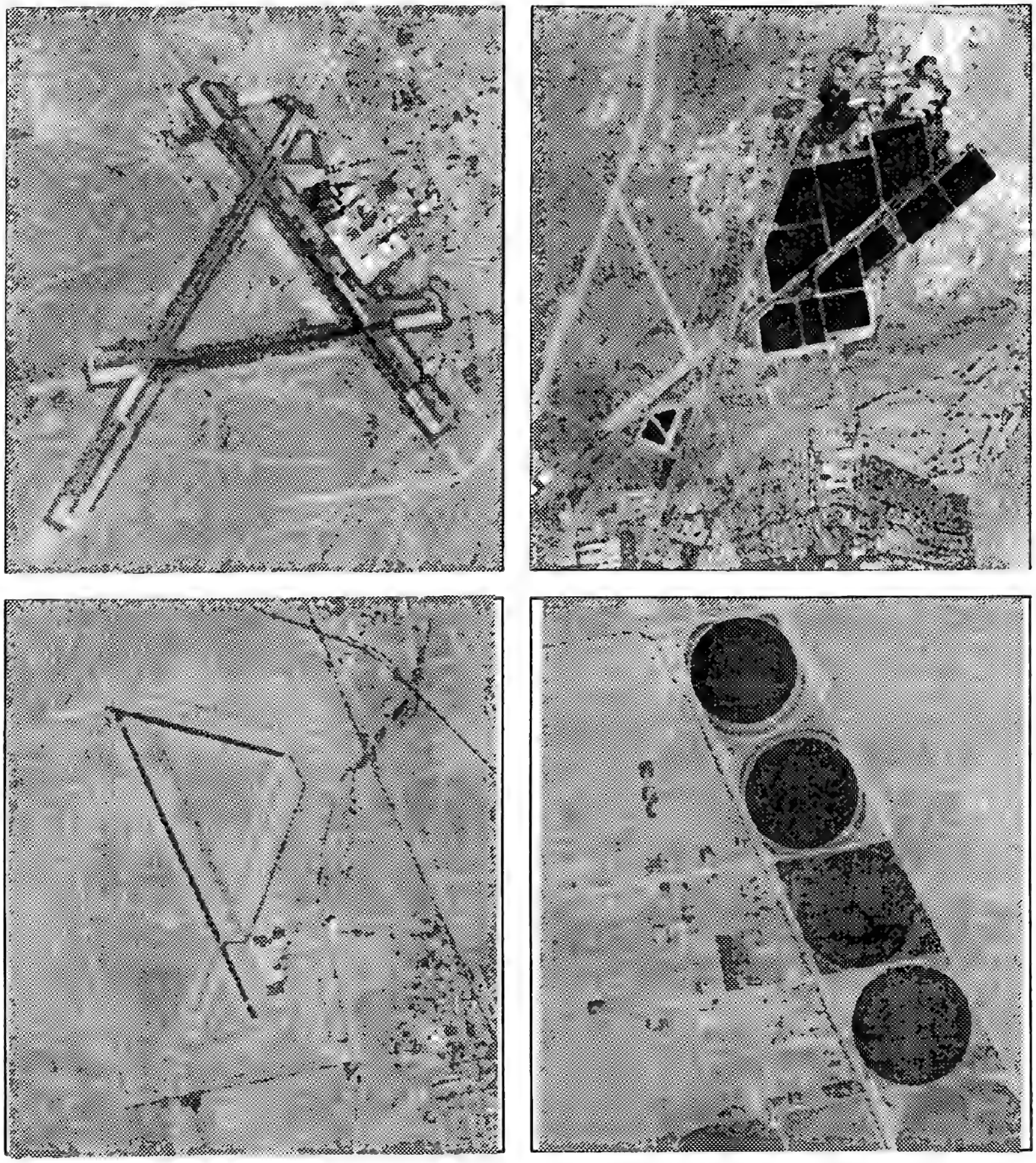

FIGURE 6. STANDARD TARGETS FOR TEMPLATE MATCHING--SPOT IMAGES

UPPER LEFT: CHINA LAKE AIRFIELD UPPER RIGHT: SEWAGE-TREATMENT PONDS
LOWER LEFT: INYOKERN AIRPORT LOWER RIGHT: CENTER-PIVOT IRRIGATION

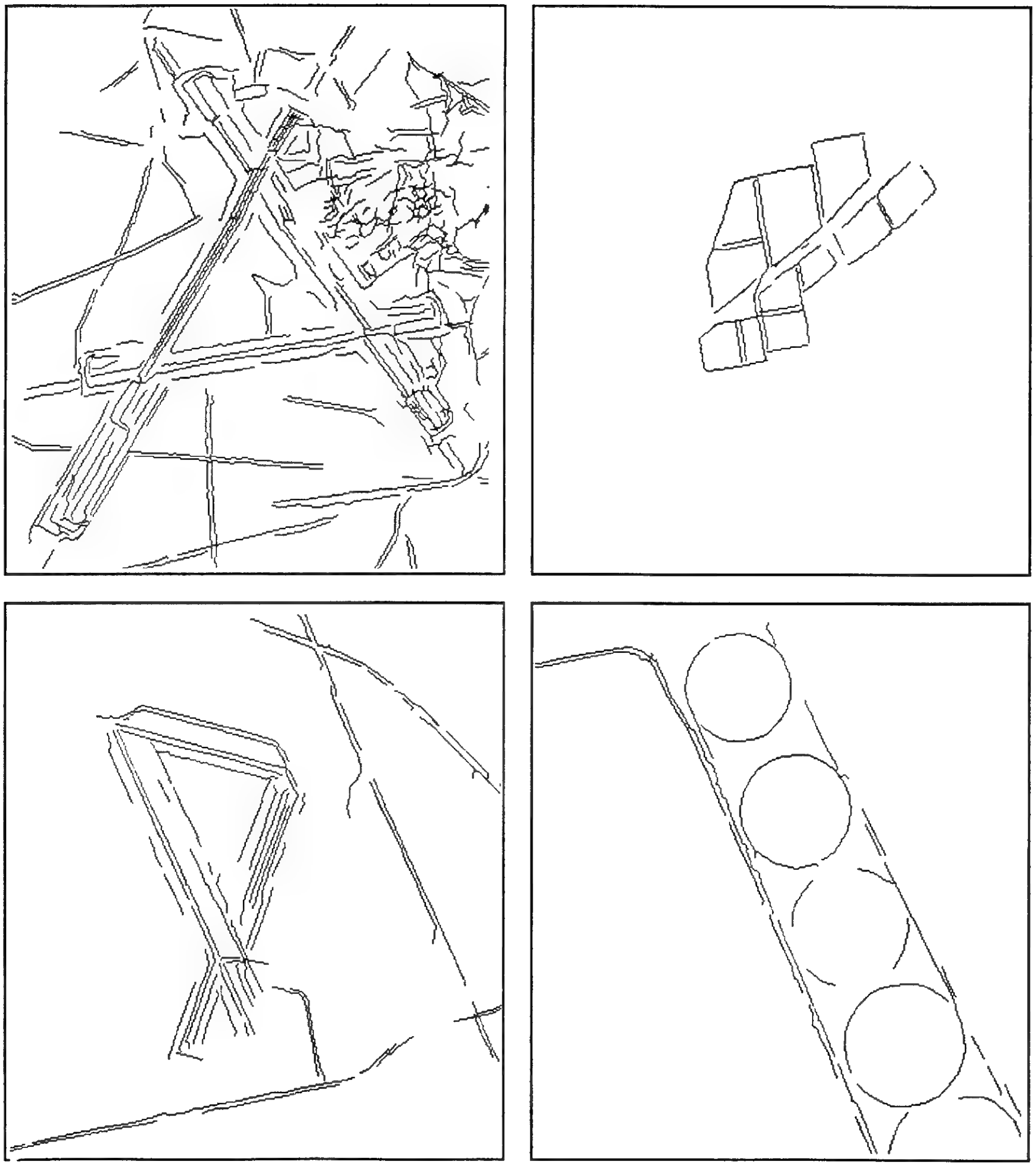

FIGURE 7. STANDARD TARGETS FOR TEMPLATE MATCHING--TEMPLATES

UPPER LEFT: CHINA LAKE AIRFIELD UPPER RIGHT: SEWAGE-TREATMENT PONDS
LOWER LEFT: INYOKERN AIRPORT LOWER RIGHT: CENTER-PIVOT IRRIGATION

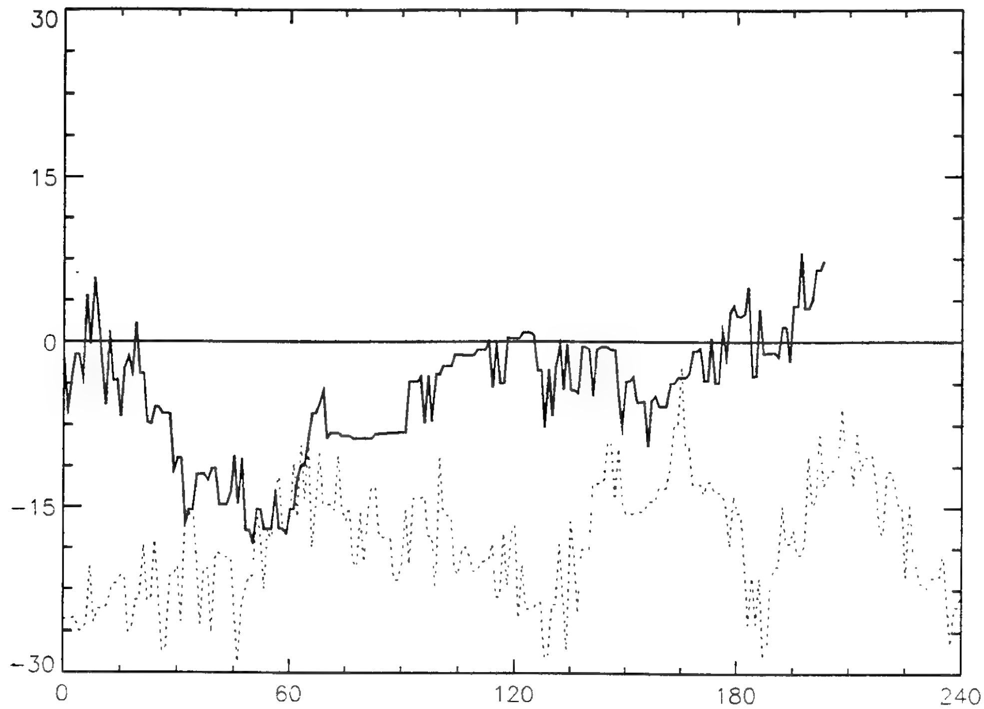

FIGURE 8. CROSSRANGE TRACKING ERROR (METERS) vs. VIDEO FRAME NUMBER

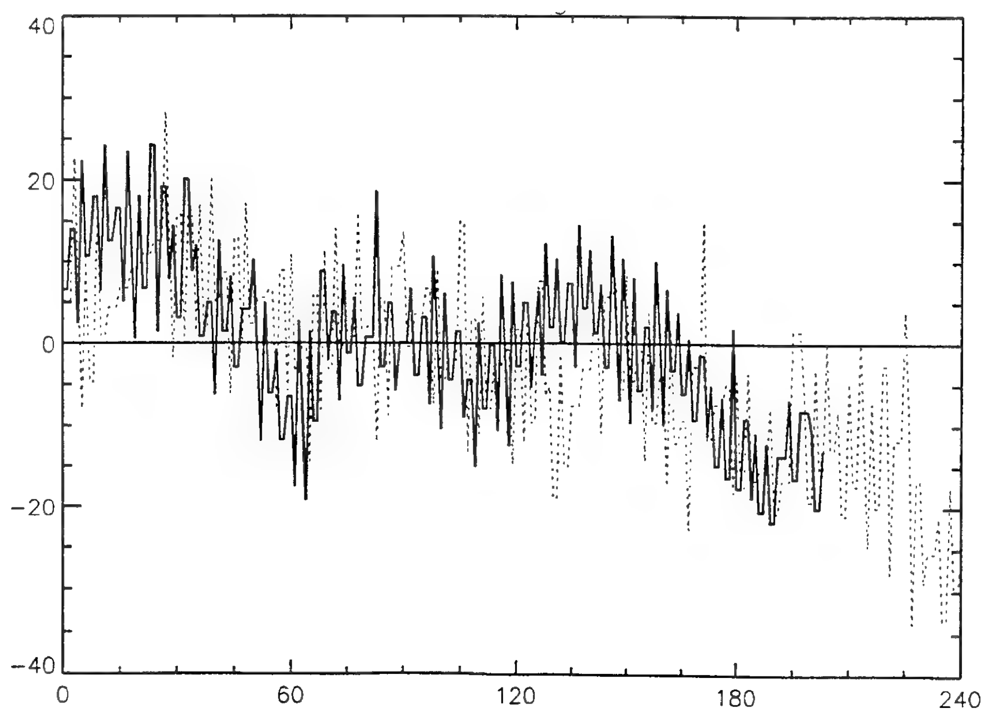

FIGURE 9. DOWNRANGE TRACKING ERROR (METERS) vs. VIDEO FRAME NUMBER

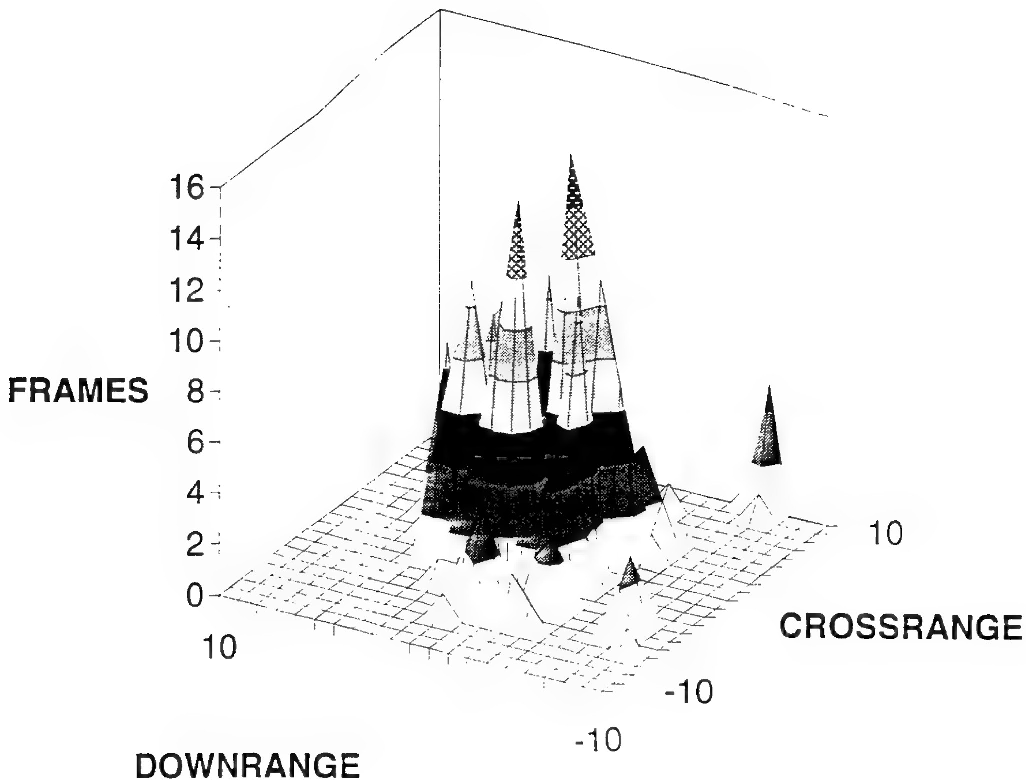

FIGURE 10. SUMMARY OF TEMPLATE-MATCHING PERFORMANCE.

Flight Test of a Low-Altitude Helicopter Guidance System with Obstacle Avoidance Capability

Richard E. Zelenka
NASA Ames Research Center, Moffett Field, CA, 94035, U.S.A.
Raymond F. Clark
U.S. Army, Command / Control and Systems Integration Directorate, Ft. Monmouth, NJ, 07703, U.S.A.
Robert G. Branigan
U.S. Army, Night Vision and Electronic Sensors Directorate, Ft. Belvoir, VA, 22060, U.S.A.

SUMMARY

Military aircraft regularly conduct missions that include low-altitude, near-terrain flight in order to increase covertness and payload effectiveness. Civilian applications include airborne fire fighting, police surveillance, search and rescue, and helicopter emergency medical service. Several fixed-wing aircraft now employ terrain elevation maps and forward-pointed radars to achieve automated terrain following or terrain avoidance flight. Similar systems specialized to helicopters and their flight regime have not received as much attention. A helicopter guidance system relying on digitized terrain elevation maps has been developed that employs airborne navigation, mission requirements, aircraft performance limits, and radar altimeter returns to generate a valley-seeking, low-altitude trajectory between waypoints. The guidance trajectory is symbolically presented to the pilot on a helmet mounted display. This system has been flight tested to 150 ft (45.7 m) above ground level altitude at 80 kts, and is primarily limited by the ability of the pilot to perform manual detection and avoidance of unmapped hazards. In this study, a wide field of view laser radar sensor has been incorporated into this guidance system to assist the pilot in obstacle detection and avoidance, while expanding the system's operational flight envelope. The results from early flight tests of this system are presented. Low-altitude missions to 100 ft (30.5 m) altitude at 80 kts in the presence of unmapped natural and man-made obstacles were demonstrated while the pilot maintained situational awareness and tracking of the guidance trajectory. Further reductions in altitude are expected with continued flight testing.

1. INTRODUCTION

The risk and crew workload inherent in flight operations near the ground or in poor weather is severe, with navigation, guidance, and obstacle avoidance demanding high attention. Flights are commonly cancelled due to weather or pilot-aircraft limitations that restrict flights to above local terrain maximums. For the military, operations at close proximity to the terrain are necessary to increase covertness while penetrating enemy territory. Increased survivability and payload effectiveness can also be achieved.

Advances in computational capacity, sensor capability, and signal processing have produced a variety of avionic aids for this flight regime. Much of the emphasis has focused on the ability to detect and avoid obstacles and terrain with passive sensors, such as forward looking infrared and low-level light television, and with active sensors like radar. Levels of automation for low-altitude flight range from head-down moving map displays of terrain avoidance (TA) clearance planes to full authority autopilot terrain following (TF) systems. Terrain Avoidance (TA) radars provide a top-down view of terrain above a given clearance plane, which the pilot can use to execute safe lateral avoidance maneuvers. Terrain Following (TF) radars allow automatic contour (constant AGL) flight by sending control commands to the aircraft for safe climb/dive over terrain or obstacles in the flight path. The pilot is also given a display for TF monitoring or for manual operation. Such de-coupled lateral (TA) or vertical (TF) maneuvering systems are operational in aircraft such as the A-7, F-111, and B-1 [1, 2]. In many of these systems, the pilot is obligated to perform functions such as navigation and guidance while monitoring the TF or TA system. The integration of these functions in a synergistic manner is a difficult challenge, primarily due to their mission, aircraft, and sensor specific nature.

A technology development program at NASA Ames Research Center in helicopter flight automation [3] has included the development of a low-altitude, terrain following/terrain avoidance (TF/TA) guidance system for helicopters [4]. The system employs terrain elevation maps in calculating its guidance trajectories. By applying a cost function over an intended route between waypoints, a three-dimensional TF/TA route may be calculated in real-time. The minimization of radiated energy from the aircraft is of concern during military operations where covertness is crucial, and is a prime motivation for using stored digitized terrain elevation maps for navigation or guidance.

After evaluation in several piloted simulations, this TF/TA guidance system was implemented for flight evaluation with the U.S. Army Command/Control Systems Integration Directorate, Ft. Monmouth, NJ, aboard their NUH-60 STAR (Systems Testbed for Avionics Research) helicopter. To improve above-ground-level aircraft positioning, a Kalman filter was developed which blends radar altimeter measurements, navigation system vertical position, and stored digital terrain data. When augmented with this radar altimeter filter, operations to 150 ft (45.7 m) above ground level (AGL) altitude in good visibility at 80 kts were achieved in flight [5].

To allow flight at even lower altitudes, a forward-looking sensor must be incorporated to locate unmapped obstacles and provide a near-field, look-ahead capability. In this work, a wide field of view laser radar sensor was integrated into the guidance system. The sensor's returns were used to generate an inertially referenced, aircraft centered obstacle database. The trajectory was then altered to avoid terrain and obstacles along its path, allowing for reduced altitude operation and adding an

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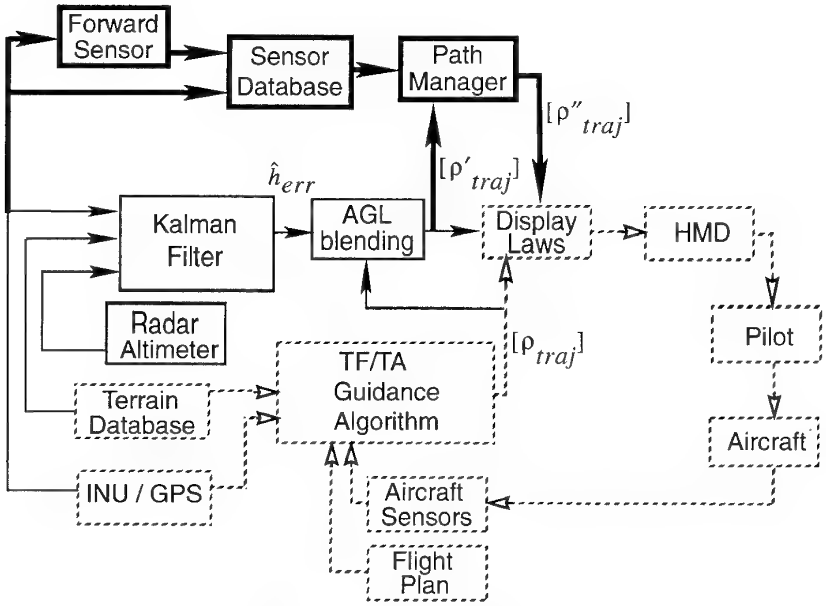


Baseline (TF/TA) Guidance System
Kalman Filter Augmented (TF/TA) Guidance System
Forward Sensor Augmented (TF/TA/OA) Guidance System

Fig.1. Guidance System Block Diagram.

obstacle avoidance (OA) capability to the guidance system.

The paper begins with a description of the low-altitude helicopter guidance system, as it evolved in three phases; 1) the baseline terrain map-based system, 2) the radar altimeter Kalman filter system, and 3) the forward sensor equipped system, which added an obstacle avoidance capability. The integration of this obstacle avoidance enhanced system is then detailed, followed by early flight test results.

2. GUIDANCE SYSTEM DESCRIPTION

The low-altitude helicopter guidance system will be described through its three phases of development, each developed in motion-based, piloted simulation and then evaluated and improved through flight test. The phases build upon one another and progressively increase in complexity and capability. Figure 1 is a combined block diagram of the guidance system through its development phases.

2.1 Baseline (TF/TA) Guidance System

The baseline guidance system computes in real-time a valley-seeking TF/TA trajectory based on mission requirements, aircraft performance capabilities, airborne navigation, and digitized terrain elevation data (Fig. 1). The system's trajectory generation algorithm maintains a cost function that seeks to minimize mean sea level (MSL) altitude, heading change from a straight line nominal path between waypoints, and lateral offset from the nominal path. The cost function is applied to candidate trajectories from the current aircraft position over discrete pitch and roll angles. The lowest cost function trajectory (for the next 30 s) is then selected [4]. Adjusting constants of the cost function allows varying degrees of weighting to be applied to each performance criterion. The pilot selects aircraft performance limits and constants for the system. These include maximum bank, climb and dive angles, normal load factor, and desired velocity and set clearance altitude. Set clearance altitude is that AGL altitude to which the guidance algorithm will nominally seek. By severely penalizing, for example, those trajectories that deviate from the straight line nominal course (in heading and position), a straight line contour trajectory is generated. Such flight exclusively in the vertical plane is termed terrain following (TF) flight. Decreasing the penalty on these same two parameters allows lateral movement, and yields a meandering terrain following / terrain avoidance (TF/TA) flight profile. A general flight plan, consisting of a series of course waypoints, is supplied by a mission planner or simply input by the crew, and can be changed in flight. The mission planner, if supplied with ground based threat information, will choose course waypoints sensitive to these hazards.

The trajectory generated by the guidance system is presented symbolically to the pilot through a helmet mounted display (HMD), the Integrated Helmet and Display Sighting System (IHADSS). The Honeywell IHADSS is standard equipment for the U.S. Army's AH-64 Apache helicopter. A simplified pictorial of the pilot presentation symbology on the head-tracked HMD is shown as Fig. 2, which presents a climbing left turn trajectory. The pathway troughs and phantom aircraft are drawn in inertial space along the desired trajectory. The troughs are 100 ft (30.5 m) wide at the base, 50 ft (15.2 m) tall, and 200 ft (61.0 m) wide at top, and are drawn in 1 sec increments of the trajectory out to 8 s, based on the aircraft's airspeed. The top center of each pathway is the desired, computed trajectory. The phantom aircraft flies at the top center of the forth trough

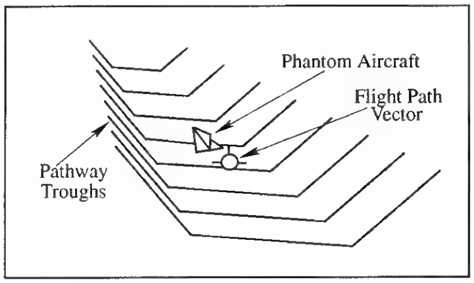


Fig.2. Guidance System Symbology.

(the desired trajectory 4 s in the future). The aircraft's flight path vector is also drawn on the helmet mounted display, as predicted 4 s ahead. Hence, by tracking the phantom aircraft with the flight path vector, the pilot attempts to fly the desired TF/TA guidance trajectory. Additional aircraft status information also displayed (but not shown on Fig. 2) includes magnetic heading, engine torque, airspeed, radar altimeter, and ball and slip indicator. A horizon line, pitch ladder, and aircraft nose chevrons are also given to improve situational awareness. An airspeed flight director tape reflects deviation from the pilot selected, desired airspeed. This symbology set was developed over several piloted, motion-based simulations with a diverse group of pilots, and gives good trajectory tracking performance with low pilot workload [6].

Although the guidance trajectory is derived from a terrain elevation map, the AGL positioning of the aircraft is found from the difference between airborne navigation mean sea level (MSL) altitude and the predicted terrain map elevation below the aircraft. The accessed value for terrain elevation is an imperfect approximation of the terrain, and is referenced using the imperfect latitude-longitude output from the navigation system. A Level 1 Defense Mapping Agency (DMA) Digital Terrain Elevation Data (DTED) database consists of a uniform matrix of MSL terrain elevation values. Unrecorded features and map horizontal shifts have been observed in flight tests [5]. Because the terrain elevation stored in the DMA database is accessed via the latitude-longitude value of the navigation system, horizontal positioning errors will reference offset terrain data. The sum of these DMA errors, combined with those of the navigation system, can lead to large errors in the predicted absolute AGL altitude.

The baseline system's performance is principally limited in its ability to position itself above the terrain, and its inability to detect and avoid unmapped obstacles, such as trees and wires. The above ground positioning limitation was found dominant and restricted flight to above 300 ft (91.4 m) AGL at the operational design speeds between 80 and 110 kts [4]. Nominal guidance trajectory settings included max climb/dive angles of $-6^\circ \le \gamma_{max} \le 6^\circ$, vertical load of $\pm 0.25g$ from nominal, and bank angle of $20^\circ < \phi_{max} < 20^\circ$. This baseline system was flight tested in day and night VFR conditions.

2.2 Radar Altimeter Augmented (TF/TA) Guidance System

As discussed, combined vertical navigation and terrain database errors in the proposed flight test area established a minimum AGL altitude ceiling of 300 ft (91.4 m). Such flight altitudes greatly compromised the benefit and effectiveness of the TF/TA guidance system, particularly to the military helicopter community, where operations restricted to such mid-level altitudes would not justify its cost and complexity.

The dashed blocks of Fig.1 detail the extension to the baseline TF/TA guidance system resulting from a Kalman filter augmentation. The predicted AGL altitude, calculated as the difference in the navigation system MSL altitude and the stored map terrain elevation, together with the radar altimeter measurement, are blended in a Kalman filter to yield an estimate for the difference error from the predicted AGL altitude [7]. This difference error value, $\hat{h}_{err}$, is then used to alter the terrain elevation database referenced guidance trajectory at the AGL-error blending block of Fig. 1. In order to ensure a smooth symbology presentation of the guidance trajectory to the pilot, the change in the value of $\hat{h}_{err}$ is ramped in linearly over the 8 troughs presented. That is, (after initialization) the eighth trough is altered in vertical position by the full change in $\hat{h}_{err}$, but the first trough is only moved by 1/8 of this $\Delta\hat{h}_{err}$. Such "ramping" does introduce a lag in the trajectory symbology, although the scheme is bounded at the eighth trough by the current value of $\hat{h}_{err}$. The solely airborne navigation and stored terrain elevation database referenced trajectory of the baseline system ($[\rho_{traj}]$) is modified with respect to the value of $\hat{h}_{err}$ to produce $[\rho'_{traj}]$. This modified trajectory is then presented to the pilot using the existing display laws and symbology.

The Kalman filter processing of the radar altimeter measurement was found robust and accurate in modifying the vertical position of the baseline terrain-referenced guidance system trajectories. The enhancement produced trajectories more reflective of the topography and allowed for lower altitude operation than that of the baseline guidance system. The minimum flight altitude was reduced from 300 ft (91.4 m) AGL altitude to 150 ft (45.7 m) at operational speeds from 80 to 110 kts [5]. Flight restrictions for the terrain-referenced guidance system were now governed by pilot obstacle detection and avoidance, which can be assisted by a forward-looking sensor.

2.3 Forward Sensor Augmented(TF/TA/OA) System

The forward sensor enhancement to the NASA/Army guidance system involved the addition of three distinct components; 1) a wide field of view forward looking laser radar, 2) a terrain/obstacle database generated from sensor returns, and 3) a path manager, which modifies the guidance trajectory if necessary after querying the sensor database (Fig. 1).

2.3.1 Forward Sensor

The forward sensor integrated was the Northrop Obstacle Avoidance System (OASYS) prototype sensor developed by the U.S. Army Night Vision Electronic Sensors Directorate (NVESD), Ft. Belvoir, VA. The OASYS uses a laser radar to locate obstacles in a 25° by 50° field of view (FOV). The sensor attempts to detect all obstacles in this FOV, particularly wires. Extensive details of the design, development, and flight evaluation of the OASYS can be found in [8, 9], and will only briefly be described here.

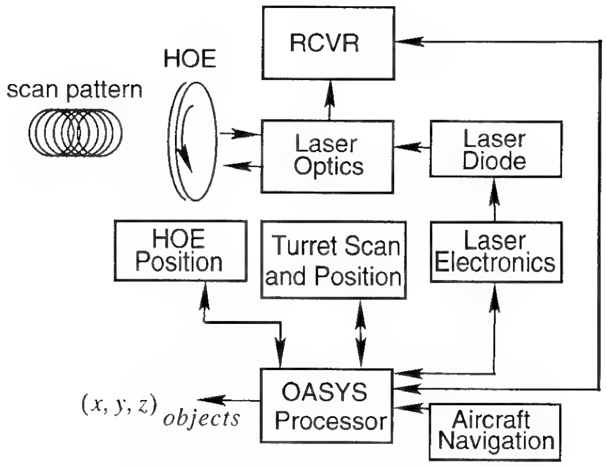


Fig. 3. OASYS Functional Schematic.

Figure 3 presents a functional schematic of the OASYS sensor. The monostatic transmitter/receiver employs an 850 nm Gallium Aluminum Arsenide diode and avalanche photodiode detector. The laser optics output a collimated circularly polarized beam to a Holographic Optical Element (HOE). The HOE diffracts this beam from nominal to 12.5°, and rotates to yield a scanning beam of 25°. By scanning the sensor in azimuth by 25°, a 25° by 50° field of view is achieved. The complete field of view is covered in 0.75 s. The sensor is designed to be eye-safe at the 6.0 in aperture, and has a maximum range of 1968.5 ft (600 m) [8].

The range of any active sensor, including the OASYS ladar, is a function of many parameters. Target characteristics, atmospheric conditions, and wave incidence angle all greatly impact detection and range performance. The OASYS was designed to detect a one inch diameter, wet wire at a 60° incidence angle at 1312.3 ft (400 m), in 6561.7 ft (2 km) visibility while flying at night. This was the design operating scenario. Performance of all laser wavelength sensors are severely limited in fog and rain. The OASYS program emphasized nighttime operations, and hence the OASYS sensor system was optimized for the night environment. Daytime performance is expected to be slightly degraded [9].

For use in the NASA/Army TF/TA guidance system, only the OASYS sensor's valid detection returns are required. These returns, either in sensor (ρ, θ, ϕ) or aircraft body $(x, y, z)_{body}$ coordinates, are necessary to construct a local, high resolution database that includes the obstacles and terrain identified by the OASYS ladar. By considering the digital map based TF/TA guidance trajectory in this OASYS-determined database, modifications can be made to the trajectory that provide an obstacle avoidance capability to the TF/TA guidance trajectory.

2.3.2 Sensor Generated Database

The terrain and obstacles located by the forward sensor are stored in an inertially-referenced grid system with grid resolution of 33 ft (10.1 m). The area considered by the guidance system is 4921 ft (1500 m) square and is periodically shifted through the grid system such that its center position remains approximately below the aircraft. The database is updated with a group of OASYS detected "objects", nominally at 10 Hz. The number of objects in each group varies with the scene content, aircraft orientation, and environmental conditions. In this context, objects includes any detected obstacles, both man-made (e.g. wires, buildings,) and natural (e.g. ground itself, trees). The OASYS objects are received in aircraft body referenced $(x, y, z)_{body}$ coordinates, and are immediately transformed into (world) inertial coordinates (x, y, z).

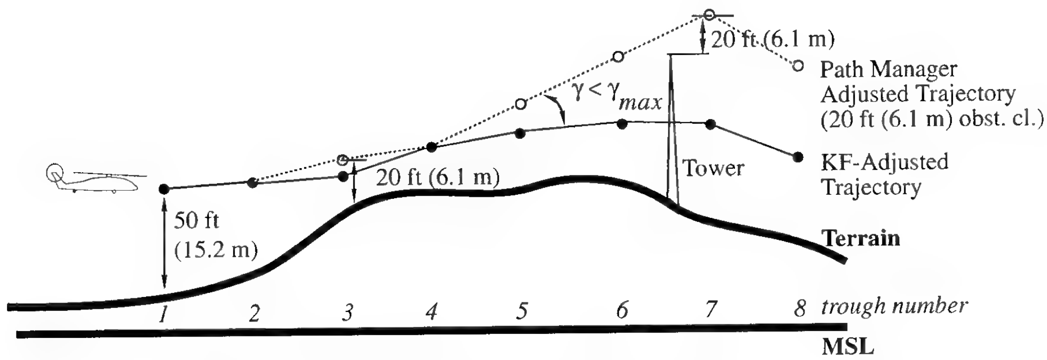
The 32.8 ft (10 m) quantized grid of the database to which each detected OASYS sensor object belongs is then determined. At this point, a simple setting of the particular grid cell to the elevation (z) value of the corresponding object might seem logical. This is equivalent to assuming a perfect sensor and perfect navigation, i.e. that every sensor detection is valid and has been transformed without error, which is unfortunately not the case. Over-writing any previous sensor objects in a particular grid would also dismiss all previous elevation measurements of the grid cell.

Several approaches to blending of multiple sensor units were considered. The fundamental trade-off is to develop a processing scheme that will perform adequate noise rejection while maintaining elevation sensitivity in each grid. This is especially difficult and important for storing obstacles where two distinct elevation values exist at the same inertial (x, y) location (i.e. an overhanging wire and the ground below it). Blending measurements using the maximum likelihood approach, the maximum elevation value for each grid, and hybrids between these two have been developed and implemented. The maximum likelihood algorithm calculates the elevation value for a particular grid which maximizes the probability of the elevation measurements to that grid, taking in statistical properties of the measurements known a priori [10]. This method has the advantage of drawing on all measurements recorded for a given grid cell, but requires more computational memory and processing. Note that many other statistically-derived state estimation schemes require the time at which each measurement was taken to be known, a value that is not provided by the OASYS sensor.

Such sensor return blending techniques, and others still under development, have a great impact on the performance and pilot acceptability of our forward sensor enhancement to the helicopter guidance system.

2.3.3 Path Manager

The path manager is used to alter the guidance trajectory in the event of an altitude clearance problem, as determined by the elevations of obstacles and terrain stored in the sensor generated database. A rectangle of variable width, extended from the previous trajectory trough to the next, is located in the sensor database. Its width was nominally set to 100 ft (30.5 m), which corresponds to the width of the bottom of the trajectory troughs (Fig. 2). Note that for an aircraft flying at 100 kts, the 1 s spaced trajectory troughs translate to a separation of 169 ft (51.5 m). The highest elevation of the sensor database grids covered for each "trough comparison rectangle" is determined and used in accessing potential clearance problems with respect to the radar altimeter Kalman filter (KF) improved guidance trajectory. All adjustments made to the trajectory are in vertical position only, i.e. no lateral modifications are made.



notes: 50 ft (15.2 m) set clearance altitude depicted.
straight lines between trajectory points are for clarity of concepts.

Fig.4. Path Manager Guidance Trajectory Modification.

Note that the optimization about the cost function described earlier for the guidance trajectory is not recomputed, i.e. this is not a "closed loop" forward sensor trajectory solution.

Figure 4 schematically illustrates the steps involved in the path manager's modification to the KF-improved guidance trajectory. A 50 ft (15.2 m) set clearance is assumed for this depiction, although this is below the 150 ft (45.7 m) AGL minimum of the KF-improved system. In this case, the DMA terrain database is underestimating the terrain at times. Recall that the KF enhancement is based on airborne navigation, digital terrain data, and the (downward-pointed) radar altimeter, and has virtually no look-ahead ability. (Only that afforded by the conical beam nature of the radar altimeter and the predictive ability of the Kalman filter's state equations). As such, the baseline trajectory is altered as a result of the digital map/actual terrain difference that is present at the aircraft's present position. The more severe underestimation of the terrain that occurs in later trough locations is not addressed, nor is the tower obstacle (between troughs 6 and 7). The pilot is tasked to perform his own obstacle avoidance maneuver.

The path manager's trough comparison rectangle values, found by querying the sensor database, are used to alter the trajectory if required. The path manager compares each KF-improved trajectory trough location with the value of that trough's comparison rectangle, the difference being the AGL altitude of that trough with respect to the highest obstacle in the comparison rectangle. If the value is greater than the pilot selected "obstacle clearance value", no adjustment is performed. If, however, the trajectory trough is below the obstacle or closer than the obstacle clearance value, a vertical repositioning is required, such that the obstacle clearance value is maintained. The path manager now determines if the repositioning of that trough alone is sufficient, or if others must be altered. This decision is driven by the flight path angle required of the guidance trajectory to achieve the desired obstacle clearance. If the new vertical position of the effected trough results in climb and dive angles below the maximum γ selected (for the baseline trajectory), only the effected trough is repositioned. This is the situation depicted in Fig. 4 for trough 3. (Note that the obstacle clearance value in Fig. 4 has been set to 20 ft (6.1 m)). For trough 7 of Fig. 4, a higher vertical adjustment is required, and hence additional upstream and downstream troughs are adjusted. Should the obstacle be so high that even progressively altering every trough does not clear the obstacle, the γ_{max} constraint is removed and all troughs are moved to that (constant) value of γ that will clear the obstacle at the desired setting.

This approach for integrating a forward obstacle avoidance sensor into the terrain referenced guidance system has the advantage of using the existing flight proven components of the guidance system, and was developed through motion-based, piloted flight simulation [11]. The repositioning of the trajectory only vertically also allows a thorough understanding of sensor characteristics and sensor database construction techniques to be understood through flight test prior to possibly more sophisticated (i.e. lateral with vertical repositioning) techniques being attempted.

3. AIRCRAFT INTEGRATION

The low-altitude forward sensor augmented (TF/TA/OA) system was implemented and flight tested aboard a modified Sikorsky UH-60A Blackhawk helicopter. The Systems Testbed for Avionics Research (STAR) aircraft is operated by the U.S. Army Command / Control and Systems Integration Directorate, Ft. Monmouth, NJ. The OASYS laser radar sensor was mounted on the nose of the helicopter, while a FLIR camera was contained in a chin turret (Fig. 5). A color TV camera was rigidly mounted inside the cockpit between the pilots. The components of the NUH-60A STAR are cataloged in Table 1.

The NUH-60A STAR hosts the Army Digital Avionics System (ADAS). This system allows fully integrated control and display capabilities for the pilot and co-pilot through two identical pairs of multi-function displays. These displays provide digital monitoring of aircraft state and instrumentation and associated control. A flight engineer station at the rear of the aircraft includes an additional ADAS display for flight test direction and control. All components of this network are connected through a 1553B interface. The computer system architecture is given as Fig.6.

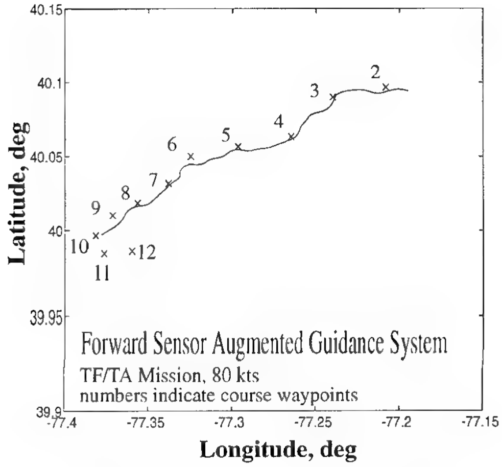


Fig.7. Flight Test Ground Track.

experimental flight test mission would begin at waypoint 2 in the northeast, and follow a meandering trajectory to the southwest to waypoint 9. After disengaging from the tracking of the trajectory, the pilot loops around waypoints 9 through 12 while the system is reconfigured for another test condition, and then flies another mission from waypoints 8 through 2. A typical 80 kts flight covers the 20 n.mi. (37.1 km) course in about 20 min. Note that because the guidance algorithm computes a trajectory solution in real-time based on the aircraft state, stored terrain data, mission flight plan, and aircraft state history (Fig. 1), no two test missions will be identical.

The vertical flight profile of a representative portion of an 80 kts terrain following (TF) mission in the Harrisburg area is shown as Fig. 8. Terrain following flight, or contour flight, is flown at constant heading between waypoints with only vertical maneuvering. The ground track of such flight results in straight lines between waypoints. The upper (dashed) line traces the aircraft MSL altitude while flying the guidance system with 50 ft (15.2 m) set clearance altitude and 50 ft (15.2 m) obstacle clearance height. The middle line tracks the desired (or "commanded") trajectory MSL altitude, which is that computed by the trajectory algorithm as modified by the forward sensor dependent path manager and presented to the pilot ($[\rho''_{traj}]$ of Fig. 1). The lowest line is the "truth" measurement of the terrain elevation, which is calculated as the aircraft's MSL altitude minus the radar altimeter measurement. Vertical navigation error during this period was 23 ft (7.0 m), with radar altimeter error of ~ 8 ft (2.4 m). Note that the relative position of the MSL positions (aircraft and pathway) to the terrain are only off by the accuracy of the radar altimeter, while absolute distances are affected by both vertical navigation and radar altimeter. Note that the radar altimeter generally measures height above the forest floor, not height above the treetops (canopy height). As such, the actual AGL height above the forest canopy is about 50 ft (15.2 m) lower than shown here, due to the average 50 ft (15.2 m) tree height in this region of the test area.

The commanded (path manager corrected) pathway of Fig.8 presented a smooth but aggressive trajectory that is between 50 and 100 ft (15.2 and 30.5 m) AGL. Such AGL altitude is expected, given the 50 ft (15.2 m) set clearance and 50 ft (15.2 m) obstacle clearance. Terrain undulations are recognized and reflected in the pathway placement. Occasional areas where the guidance pathway appears too high or is not reconcilable with the terrain are most likely due to local foliage effects, i.e. a tight, higher concentration of trees. This area of the course was densely packed with trees and clear of man-made obstacles.

The aircraft's MSL location of Fig. 8 is suspiciously higher than that commanded by the guidance system. There are two principle reasons for this. First, the forward sensor enhanced TF/TA/OA guidance system inte-

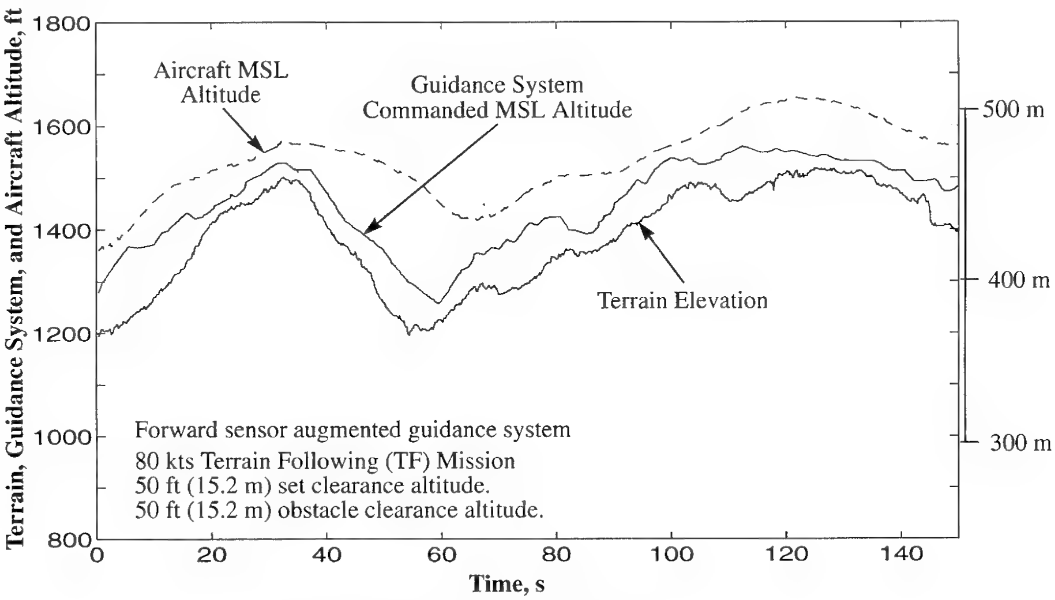


Fig.8. Flight Test Vertical Profile.

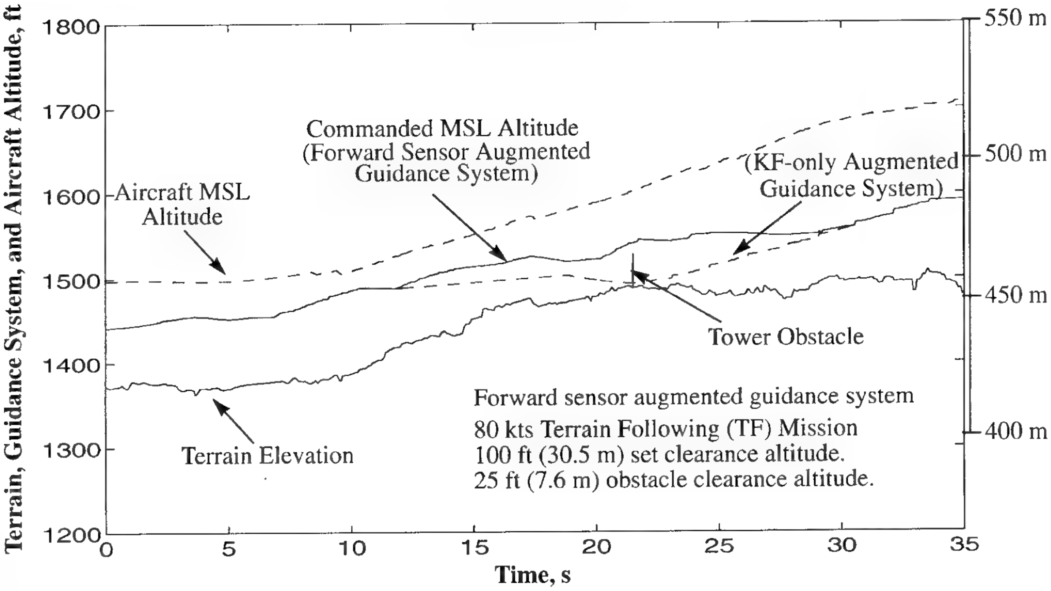


Fig.9. Flight Test Vertical Profile with Tower Obstacle.

gration was completed in early June 1994, with first flights occurring in late June. Hence, test pilots were asked to fly conservatively during this first phase of the system, and flew above the commanded trajectory pathway troughs during the majority of configurations evaluated. During the next phase of flight tests, such a safety factor will be gradually removed. The second cause for the difference between the aircraft and guidance pathway position is that the pilot can never track the symbology perfectly, and at times will override the recommended pathway. Circumvention of the commanded trajectory occurs most often when a pilot "short-cuts" the suggested guidance trajectory, when a ridge is crossed followed by rising terrain. This was the case in Fig. 8 when the ridge at time ~35 s was crossed. Here, the pilot applied safety factor of ~ 50 ft (15.2 m) above the guidance was extended even further between time 40 to 60 s.

Figure 9 traces 35 s of flight toward the end of a TF mission conducted in the Harrisburg area. The guidance system was set for 80 kts flight, set clearance at 100 ft (30.5 m), and obstacle clearance at 25 ft (7.6 m). Vertical navigation error during this period was 20 ft (6.1 m), with radar altimeter error of ~ 8 ft (2.4 m). The course brought the aircraft just to the right of waypoint 2, a communications tower surveyed to be 1527.9 ft (465.7 m) MSL (approximately 40 ft (12.2 m) above the truth terrain elevation). The middle solid line records the commanded guidance trajectory position of the forward sensor augmented system, which is that trajectory presented to the pilot. The dashed line near it is the guidance trajectory of the radar altimeter Kalman filter improved trajectory *without* the forward sensor modification, i.e. *prior to path manager modification* (Fig. 4). This was recorded to explicitly study the path manager and forward sensor augmentation near isolated obstacles, such as a tower. (Note that the 100 ft (30.5 m) set clearance altitude selected is below the minimum clearance altitude of the KF system, established at 150 ft (45.7 m)).

From Fig. 9 it is clear that the forward sensor has detected the tower obstacle, sent its location for processing to the sensor generated database, and been used by the path manager in adjusting the guidance trajectory. The forward sensor augmented system commands a higher altitude trajectory than the KF-only system about 10 s prior to the obstacle, or about 1350 ft (411.5 m) ahead of the obstacle at this 80 kts airspeed. The pathway is adjusted to vertically clear the hazard and is eventually brought back down to the KF altered pathway position. Such detachment and reattachment is expected as discussed previously (Fig. 4). Again, pilot tracking of the trajectory was intentionally conservative and resulted in the 50 to 100 ft (15.2 to 30.5 m) higher height difference between the guidance trajectory and actual aircraft piloted positions.

5. DISCUSSION

The results from the early flight tests are very encouraging, and demonstrate the OA capability added as a result of the forward sensor integration. Flights to date have extended the operational environment of the TF/TA guidance system to 100 ft (30.5 m) altitude, 80 kts flight in the presence of unmapped obstacles. Flights in the Lakehurst, NJ area across high tension wires demonstrated the ability of the OASYS sensor and the guidance system to detect and react to unknown wire obstacles.

Several lessons were learned regarding the forward sensor and integration technique during this first phase of testing. The system is very sensitive to the characteristics of the sensor generated database. Initially, the highest value detected by the sensor for a given database grid was retained regardless of prior returns to that grid or the magnitude of that return. This was thought to be a conservative approach that would ensure that all possible height hazards were stored in the database. This scheme, however, resulted in an excessively noisy database, which in turn generated a constantly shifting tra-

jectory, unacceptable to the pilot for HMD presentation and unobtainable for pilot tracking. Efforts to address this noise versus obstacle sensitivity resulted in the use of the maximum likelihood approach for blending multiple sensor returns to the same grid, while simultaneously monitoring the highest value returned from each grid. If this highest value exceeds a given threshold limit above the maximum likelihood estimate, that value is assigned to the grid cell.

It was also found that the pitch movement of the aircraft during the test flights would at times create azimuth swaths ahead of the aircraft where no sensor returns were recorded. This is a result of the fixed 25° by 50° FOV of the OASYS sensor. The effect was magnified whenever a hill was crested, further limiting the (relative) "look-down" ability of the aircraft-sensor system. To address this problem, the dive angle limit for the trajectory was increased ($-10^\circ \leq \gamma_{max} \leq 6^\circ$) to allow more aggressive pitch down maneuvers of the aircraft. This also addressed occasional "ballooning" of the guidance trajectory when cresting ridges.

Future flight tests of the forward sensor-enhanced guidance system will concentrate on tuning of sensor database construction techniques and path manager constraints (e.g. γ limits), as the pilots are allowed to more aggressively and closely track the pathway guidance trajectory. Early results demonstrate the obstacle avoidance capability of the low-altitude helicopter guidance system and its ability to extend the system's flight envelope to 100 ft (30.5 m) AGL altitude, 80 kts flight in the presence of unmapped obstacles, including wires, towers, and trees. A further reduction in flight altitude to 50 ft (15.2 m) is expected as the flight test program continues.

6. CONCLUDING REMARKS

1) A wide field of view laser radar forward sensor was integrated into a low-altitude, terrain elevation based helicopter guidance system. The sensor's returns were used to generate an inertially referenced, aircraft centered obstacle database. The baseline guidance trajectory was then altered to avoid terrain and obstacles along its path, allowing for reduced altitude operation, and adding an obstacle avoidance (OA) capability to the guidance system.

2) The obstacle avoidance capable system was implemented for real-time operation aboard a U.S. Army Blackhawk helicopter. The resulting guidance system was flight tested in both flat and moderately rugged terrain under a range of test conditions and obstacles, including wires, towers, and trees.

3) Early results demonstrate the obstacle avoidance capability of the low-altitude helicopter guidance system and its ability to extend the system's flight envelope to 100 ft (30.5 m) AGL altitude, 80 kts flight in the presence of unmapped natural and man-made obstacles. A further reduction in flight altitude to 50 ft (15.2 m) is expected as the flight test program continues.

Acknowledgments

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Helicopter HF Communications Using the NVIS Mode

M. Proia, IT
ELMER An Alenia Company
Viale dell'Industria, 4
Pomezia (Roma) - Italia

1. INTRODUCTION

The importance of helicopters in the battlefield scenarios is significantly increasing as the new weaponry and guidance control systems allow use of helicopters in a multiplicity of roles,ranging from anti-tank operations to rapid transportation of men and materials.

Missions are often assigned to the helicopters that require flying at close distance from the enemy positions.In these cases,low-altitude flying is necessary for survivability and this type of operation,designated as Nap-Of-Earth(NOE) flying,is a well established helicopter tactics for concealment against enemy fire.In the ordinary modes of operation,radiocommunications between the helicopter and other platforms in the tactical area are supported by the VHF1(30 to 88 MHz),VHF2(108 to 172 MHz) and UHF(225 to 400 MHz) frequency bands over line-of-sight(LOS) links.

The VHF1 band is used by the helicopter to communicate with ground forces during RECCE missions and to interact with other battlefield units for mission management and briefing.

The VHF2 band is dedicated to communications with the Base for ATC purposes,while the UHF band is universally used for Ground-Air-Ground and Air-to-Air links in Air Defense operations.As NOE altitudes for helicopters are typically in the order of a few feet,LOS conditions are seldom achieved due to interposed obstacles(such as vegetation or a hilly landscape) or simply because at NOE altitudes the distance between the communicators may well exceed the LOS range.

In this scenario precluding effective use of tactical VHF,helicopter to ground and helicopter to helicopter links can be reliably established over battlefield distances by use of the HF propagation mode known as Near-Vertical-Incidence-Skywave(NVIS),whereby an RF signal with a high angle of incidence (greater than 80 degrees) is reflected by the ionosphere back to earth producing an umbrella-type coverage. By appropriate selection of the operating frequency in 1 to 2 MHz passbands(windows) located in the 2 to 10 MHz range,NVIS provides gapless coverage over distances up to 300 km.

2. HF RADIOCOMMUNICATIONS ONBOARD HELOS

Some general considerations on airborne HF radiocommunications are in order.The use of conventional HF systems places a heavy burden on the crew,due to the lengthy procedures required to establish and maintain a reliable communication link.

This is particularly true in the NVIS mode of operation for two main reasons:

* the position of the usable "windows" is strongly dependent on the physical state of the ionosphere,more specifically on the time of the day,the sunspot number and the geographical location.

* in the NOE conditions typical of NVIS operation, the crew activities are dedicated to the control of the aircraft for reasons of flight safety.

Therefore, efficient use of HF communications onboard helicopter is subordinate to the implementation of techniques capable of relieving the operator workload through automatic frequency management procedures.
Besides frequency management,other aspects need to be considered.

To be effective, HF radiocommunications onboard helicopters must be capable of supporting the increasing data traffic requirements of the battlefield and be protected again the link quality degradations that may be caused by the propagation characteristics of the HF channel and by intentional jamming.

Selection of the appropriate antenna,a critical issue for all airborne radiocommunications,is also a major factor of efficiency for NVIS operation.The optimum NVIS antenna must have:

* adequate efficiency in the 2 to 10 MHz range
* higher gain at radiation angles near the zenith
* horizontal polarization component for NVIS communication,combined with a vertically polarized component for groundwave propagation.
  Size and geometry suitable for installation onboard helicopters.

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

3. FREQUENCY MANAGEMENT TECHNIQUES FOR NVIS OPERATION

Automatic frequency management is a fundamental requirement of many tactical and strategic applications of HF radiocommunications,as a major factor for the achievement of simple use and reliable operation.

Several different techniques have been developed,one of which,designated as ALE(Automatic Link Establishment),is codified in the MIL-STD-188-141A.
The link establishment procedures consist of:

* definition of a usable set of frequencies derived from the available long-term propagation predictions;
* link tests on the selected frequencies to compile quality assessment lists for the desired links:
* establishment of the link at the desired frequency.
The NATO Panel for STANAG 4444 has accepted the basic concepts of ALE and is working on the definition of a new system with advanced solutions in relation to link maintenance and other issues.

A prerequisite for the implementation of frequency management techniques,in the present MIL-STD-188-141A ALE and future STANAG 4444 formats,is the availability of modern radio equipment with improved performance characteristics when compared with conventional radios(higher frequency agility for example) and a new software-based capability to interact with the management function.

4. DATA OPERATION

Over the last few years,the requirements of modern warfare have produced significant innovations in the C3I function,associated with a growing use of computers and other data processing devices.

In this new operational environment,voice communication,prevalent in the past, is being gradually replaced by data communication. Today, an increasing proportion of the battlefield traffic is supported by tactical data links and many helicopter missions require transmission of sensor data to ground-based and shipboard data processors.

In this perspective, HF airborne radios must be capable of handling data operation at data rates up to 2,400 bit/sec.
LINK-11 is at the present one of the standard tactical data link in the NATO environment and radios suitable for this type of operation are integrated in airborne radiocommunication systems.

As a case in point,the Italian Navy/Royal Navy helicopter EH-101 is fitted with two HF Transceiver systems,one of which specifically dedicated to LINK-11 operation.
HF data operation is an issue of permanent interest in NATO.

Many studies have been produced to investigate different waveforms;the debate on the pros and cons of the different approaches is still open.
Efficient encryption of voice also requires prior conversion to a digital format.Digital voice based on linear predictive coding techniques(LPC-10) is standardized in STANAG 4197.

Present developments in voice coding techniques anticipate the availability of 1200 bit/sec vocoders in the next few years and the possibility of reducing the rate down to 600 bit/sec .

5. PROTECTION OF THE INFORMATION

Protection of the information has two different aspects,referred to as communication security (COMSEC) and transmission security (TRANSEC).
Communication security deals with the protection of the information contents against unauthorized exploitation, most frequently supported by highly sophisticated ESM techniques.
The solution available is to efficiently encrypt the information, following the directions provided by the NATO Security function.

Transmission security is the protection of the RF signal against intentional jamming,an enemy activity that may result in a complete loss of the information contents. The techniques accepted by NATO and currently available are based on pseudorandom frequency hopping, which has proved to be a most effective strategy against the present threat.

In STANAG 4444 slow frequency hopping waveforms are being finalized. The COMSEC and TRANSEC solutions are strictly interrelated and in effect a unified management of both is auspicable.

For HF communications,the COMSEC and TRANSEC protections must be complemented with the protection against degradations introduced by the HF channel's multipath and fading effects.

The solutions currently available are based on a combination of Error Detection And Correction(EDAC) techniques and robust modulation schemes.

6. CONSIDERATIONS ON THE NVIS ANTENNA

The investigations on the most suitable NVIS antenna have been focused on the loop-type antenna, having recognized the advantages over other antenna types.

When compared with aircraft wire and notch antennas,the loop allows to achieve a significantly higher efficiency of the overall antenna system,as the inductive reactance of the loop can be tuned with capacitors in a high-Q circuit configuration.

Laboratory tests and field trials (Ref. 2 and Ref.3) indicate an average improvement of 10dB of the loop antenna over an open wire type antenna on small size (AB-129) medium size (Sea King) helicopters, over the 2 to 9 MHz band.

In addition,the loop has the advantages of robust construction and reduced size and weight.
Physically, the HF loop antenna is a metal tube with a diameter of 15 to 30 mm and a length of several meters (a typical antenna length is 3 m), supported over the aircraft structure at a height of 0.3 to 0.5 m.

The RF excitation is applied to one end while the other end is grounded to the airframe; switches are provided to shorten the loop length for operation over the upper portion of the frequency band.

The loop antenna is characterized by two co-existent modes of operation, the loop mode (with prevalent vertical polarization) and the dipole mode(with prevalent horizontal polarization).

Groundwave propagation is supported primarly by the loop mode while the dipole mode provides very efficient NVIS operation. The radiation pattern for the horizontally polarized skywave is to a good approximation omnidirectional,the groundwave pattern is a figure-of-eight with fore and aft maxima.

Basic considerations indicate that the loop antenna should be installed in a relatively flat area of the airframe,away from openings that may impede regular current flow. When properly installed,the loop acts as an excitation source for the airframe,a circumstance that can greatly contribute to the radiation efficiency.

7. ACHIEVEMENTS

Over the last years,studies,investigations and experimentations have been conducted by Defense Agencies,scientific institutions(refs 1,2),and industrial organizations on various issues of airborne radiocommunication in connection with the NVIS mode.
As a result there is a good understanding of the fundamental operational requirements and technical aspects concerning the implementation of HF/NVIS systems onboard helicopters.

In this environment,the ELMER company in Pomezia (a long-time producer of radiocommunication and radionavigation systems for the three Services) has conducted, over the last fifteen years, a continuous activity of design,testing,simulation and field trials for the development of HF radiocommunication systems operating in the NVIS mode.

At the same time ELMER has provided technical support to other organizations involved in parallel experimentations.In one case,ELMER has participated to the design and installation of the loop antenna system on a Sea King helicopter of the Royal Aerospace Establishment U.K. (fig.1 and fig.2 and ref.2).
The results of such activity are a new family of HF radios and loop antenna systems for use onboard aircraft of different types.Details on the installation of ELMER loop antenna systems are shown in figures 3 through 7.

- Loop antenna systems

Over a period of several years,engineering work and extensive field trials have been dedicated to the optimization of several loop designs and associated tuners.At the present, ELMER possesses well consolidated design techniques and fabrication technologies in this field,reflected in a full range of products currently in use.

This includes loop antennas of different geometries and fast-tuning digital ATUs compatible with ALE and slow frequency hopping modes.Very satisfactory results have been obtained in connection with silent tuning,a very important feature of the ATU performance, which ensures quick response to frequency changes and prevents unwanted radiation of RF power.

The performance of these systems in both NVIS and conventional modes has been demonstrated by testing and field trials conducted on live installations with highly satisfactory results.

- Transceiver equipment

The basic composition of a typical HF Transceiver consists of a Receiver/Exciter Unit(common to all the configurations), a Power Amplifier Unit and an Antenna Tuning Unit.

Optionally a Pre/Postselector can be inserted in the RF connection between the Receiver/Transmitter and the Power Amplifier to provide RF selectivity in colocated installations.

200W HF Transceivers with Pre/Postselector filters are installed onboard the Italian Navy helicopter EH-101; the use of the filters allows simultaneous operation of the two onboard HF Transceivers, one dedicated to voice and one to LINK-11 operation.

The impact of the ALE,ECCM and data operation requirements is reflected in specific technical characteristics such as:

* high linearity of the transmitter and receiver processes,primarily related to data operation;

* high instantaneous dynamics of the receiver front-end to reduce distortion and blocking by strong interfering signals;

* IF filtering and modem functions based on Digital Signal Processing techniques;

* High spectral purity and stability of the internally generated frequencies by use of Direct Digital Synthesis.

The Transceivers have been designed for maximum flexibility, to allow implementation of existing techniques on a "pro tempore" basis,without impairing the capability of introducing the more advanced NATO solutions when they will be available.

At the present Transceivers are available compatible for ALE operation in accordance with MIL-STD-188-141A.

8. CONCLUSIONS

Some conclusions can be derived from the above considerations,based on the two following facts;

- The NVIS mode, for NOE operation is a well established requirement for battlefield operation of the helicopter and it will remain so in a foreseeable future.
- A NATO activity to standardize on fundamental aspects of tactical HF performance (such as Automatic Link Establishment and ECCM) is in progress. The issues are still open but the principles have already been set.

In this situation where operational requirements are defined but no established technical standards are yet available, the HF radiocommunication systems must be designed to prevent obsolescence,

The answer is a flexible hardware and software design which allows the implementation of "pro tempore" solutions based on the presently available techniques and is prepared, on the basis of the current NATO orientations, to host the hardware and software required by the final solutions.

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1. Modern HF communications for low-flying aircraft. John F. Brune and Bernard Ricciardi, AGARD Conference Proceedings N.263

2. Calculated and measured radiation characteristics of an HF loop antenna mounted upon an helicopter. J.W.R. Cox and G. Vongas RAE UK IEE 5th Intern.Conf.on HF radio systems and techniques.

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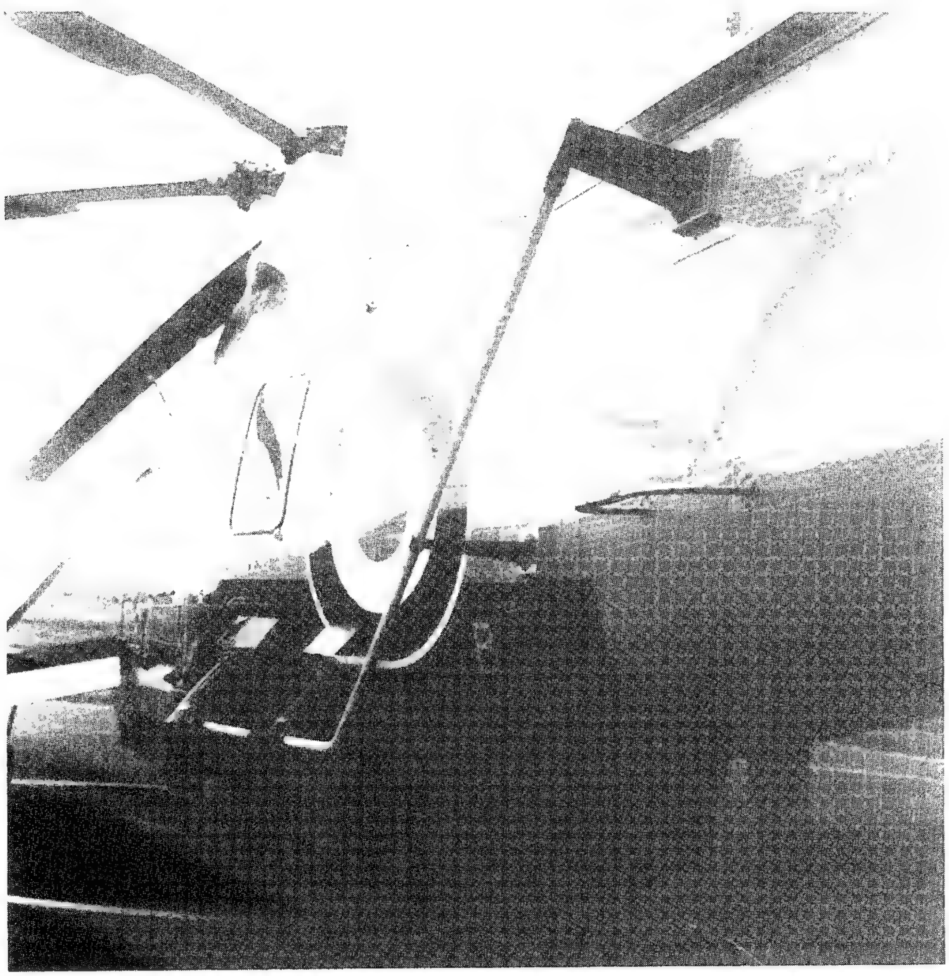


FIG. 1
SEA KING ANTENNA INSTALLATION

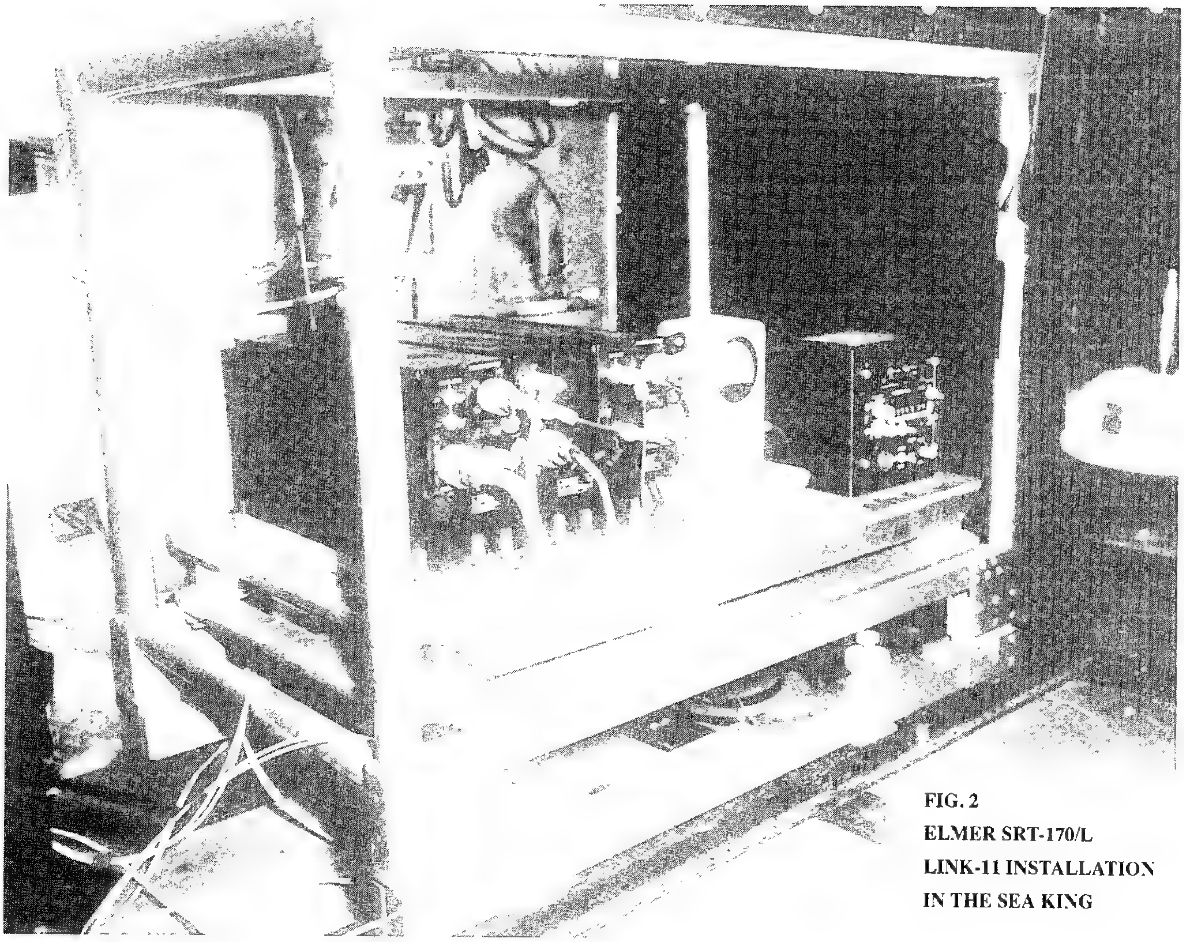


FIG. 2
ELMER SRT-170/L
LINK-11 INSTALLATION
IN THE SEA KING

FIG. 3 - HELICOPTER A129 ANTENNA INSTALLATION

FIG. 4 - HELICOPTER A109 ANTENNA INSTALLATION

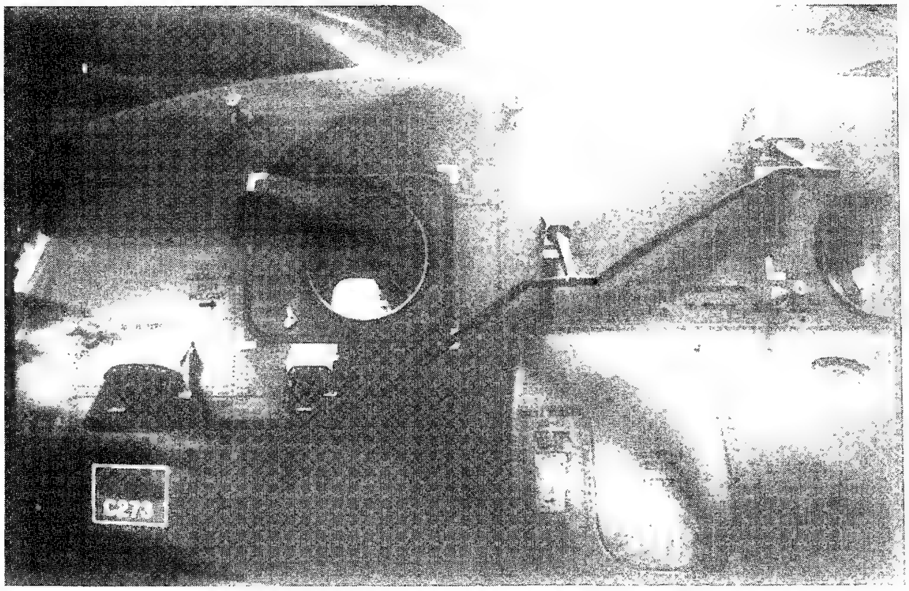


FIG. 5 - HELICOPTER HH3F ANTENNA INSTALLATION

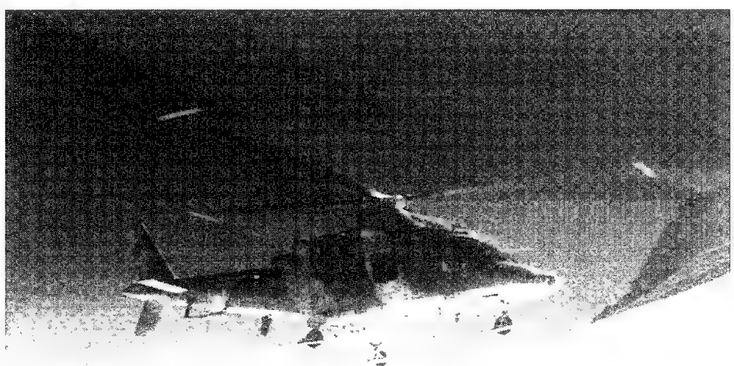


FIG. 6 - HELICOPTER A109
ANTENNA INSTALLATION

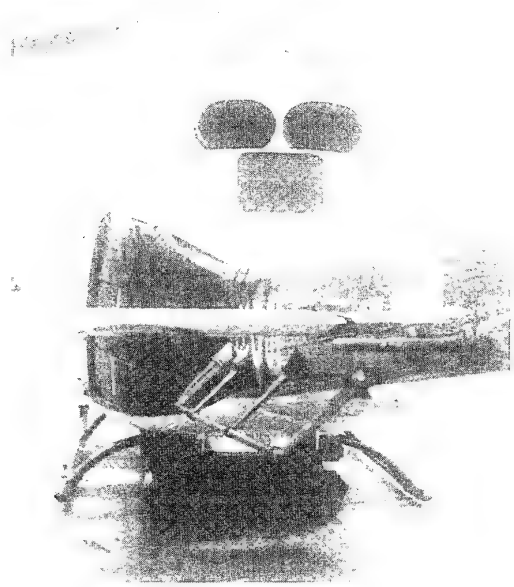


FIG. 7 - HELICOPTER AB412
ANTENNA INSTALLATION

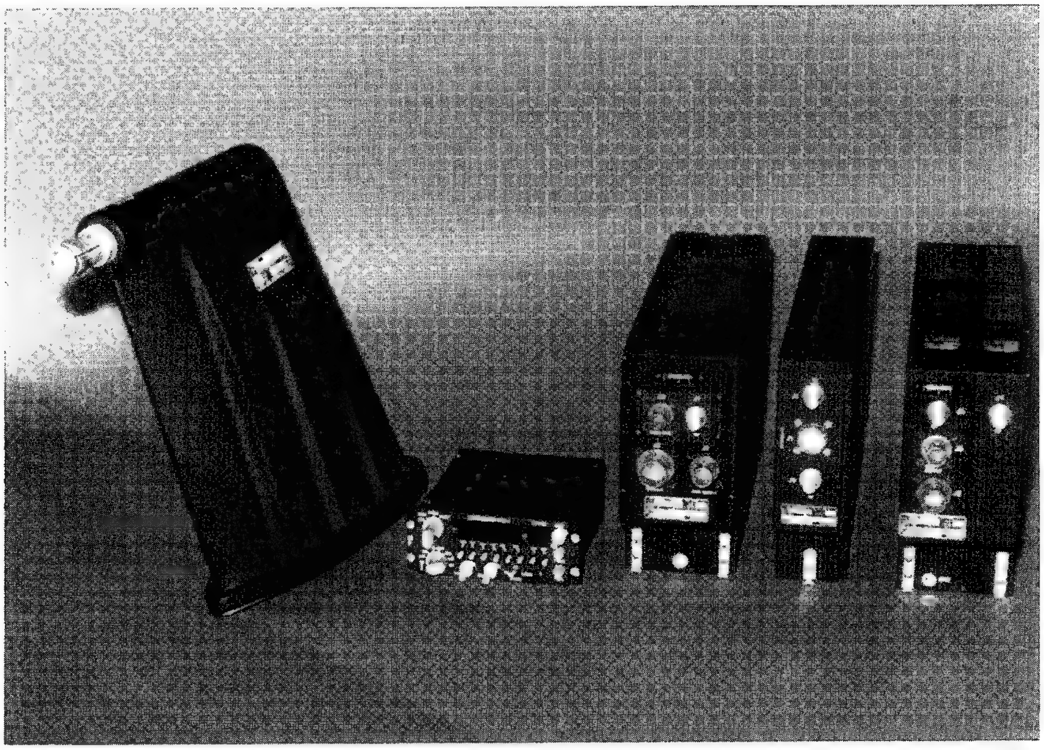


FIG. 8 - SRT-270/L HF SYSTEM

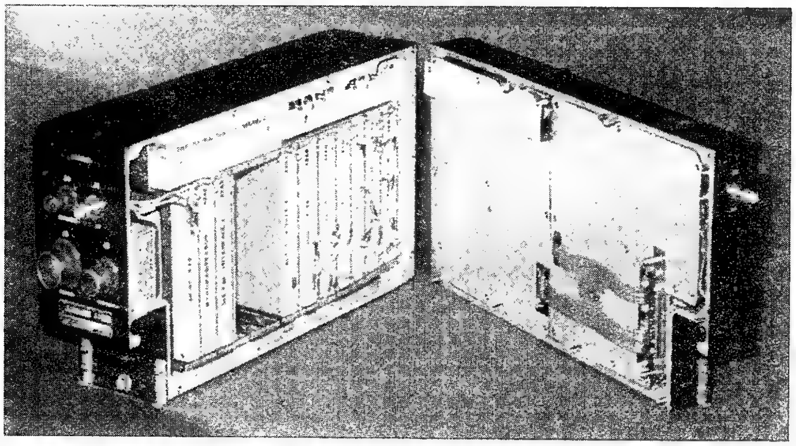


FIG. 9
SP-480/L POWER AMPLIFIER

FIG. 10
SP-649/L RECEIVER EXCITER

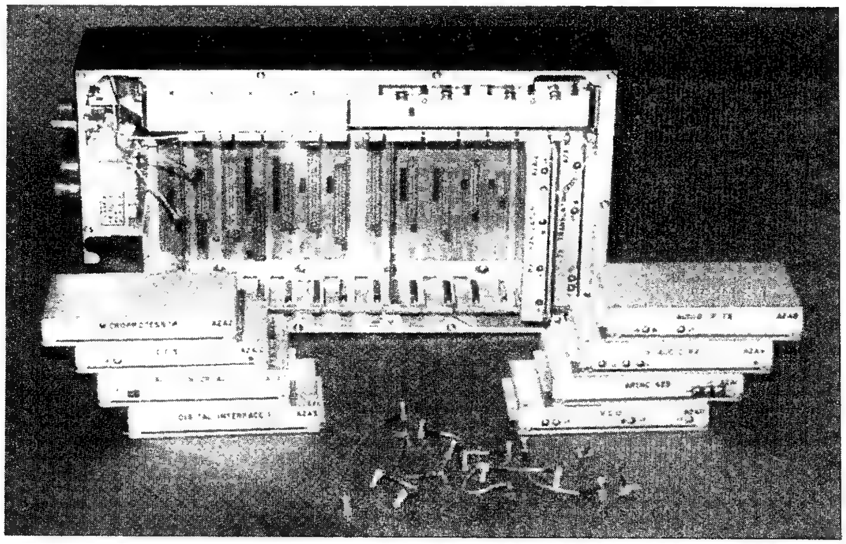


FIG. 11
SPARE SLOTS FOR GROWTH UP:
- ECCM
- ALE/ARCS
- HIGH DATA RATE MODEM

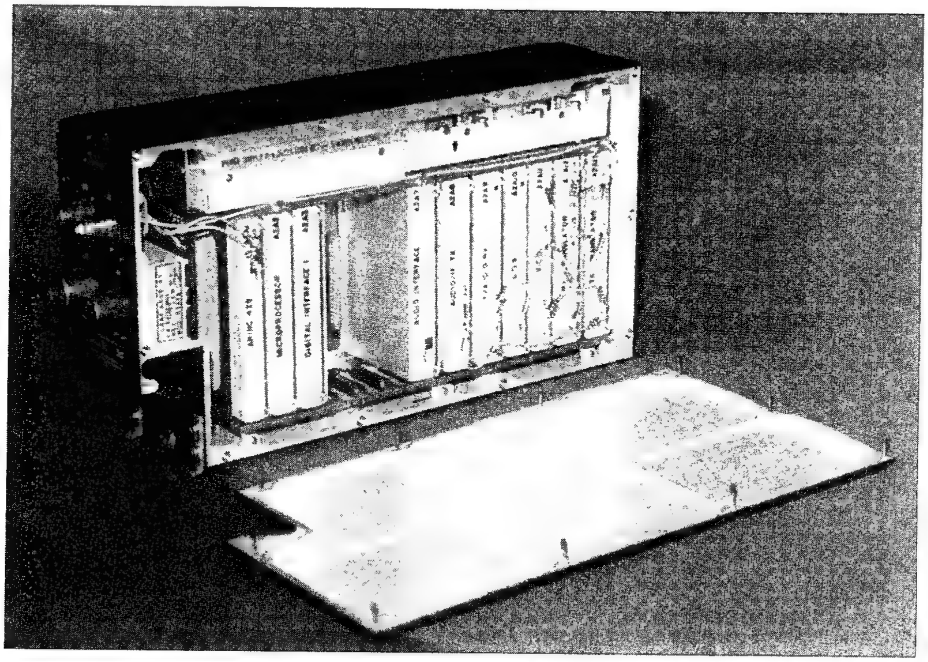
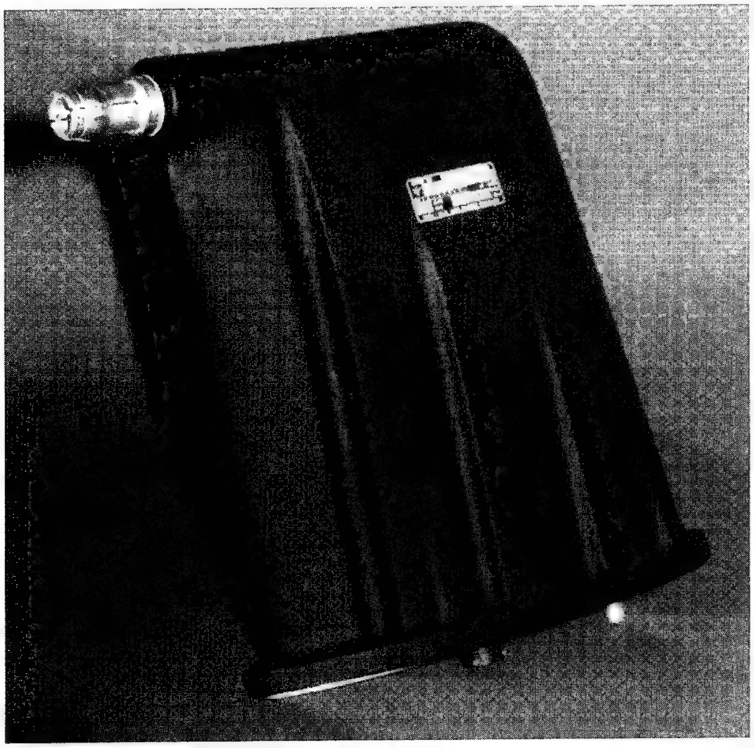


FIG. 12



ATU-1992

"SILENT TUNE" ANTENNA TUNING

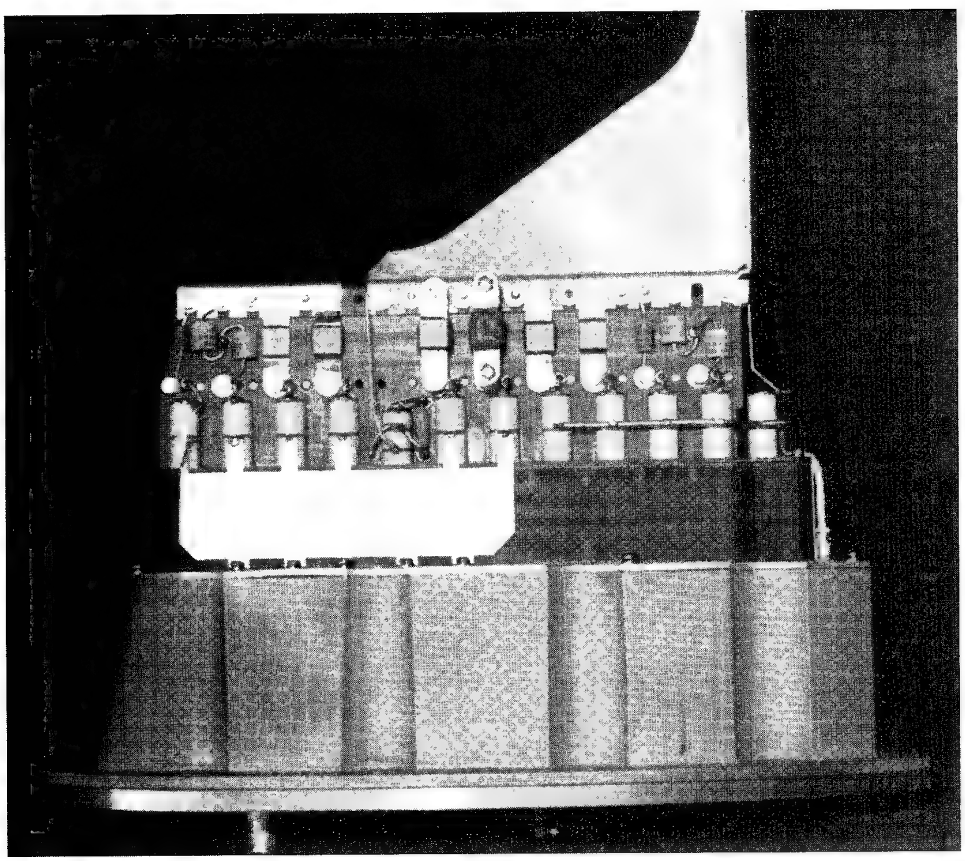


FIG. 13

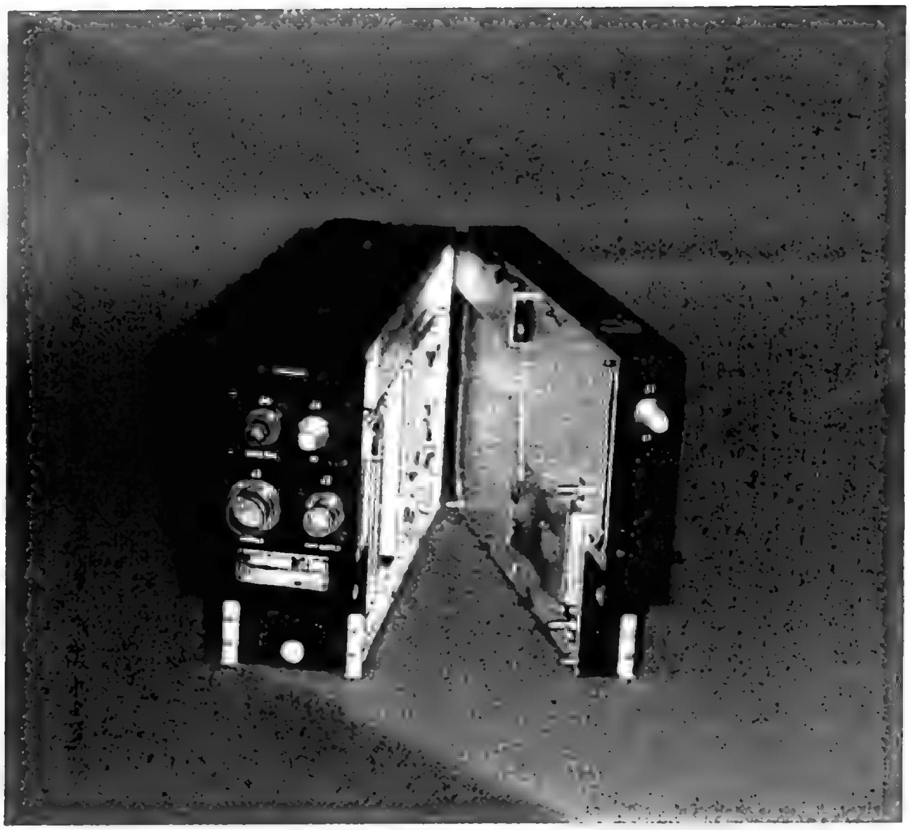


FIG. 14 - SRT-170/M HF SYSTEM
175 WATT SYSTEM FOR SMALL PLATFORMS

TACTICAL LOW-LEVEL HELICOPTER COMMUNICATIONS

Bernard V. Ricciardi
U.S. Army Communications-Electronics Command
Space & Terrestrial Communications Directorate
Fort Monmouth, NJ 07703

George H. Hagn
SRI International
1611 North Kent Street
Arlington, VA 22209

Gerald August
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

1.0 SUMMARY

The Army is rapidly moving into the 21st century with concepts for the digitized battlefield and what is called Force XXI to take advantage of new technologies and techniques. These new technologies will allow for horizontal as well as vertical integration of the battlefield communications of which the tactical, low-level helicopter communications are a part. Only now are we beginning to realize the demands that will be placed on airborne systems of the future on the integrated battlefield. For example, real-time video of targets identified by the modern aircraft (e.g.,Longbow Apache and the Comanche) will be required by future battlefield commanders of all echelons. This greatly increases the bandwidths needed for helicopter communications. Coordination with multiple joint participants on the tactical battlefield via video teleconference will occur simultaneously in such a way as to not overload the airborne battle commander. These requirements for high definition TV place further new demands on the helicopter communications systems.

Additional communications challenges have been introduced in new systems through the use of composites for low observability and weight savings; and through the increased use of, and dense system packaging of, on-board computer processing equipment which generates additional system noise and interference.

This paper identifies a systems approach to communications requirements, defines a helicopter communications system model, and describes some potential paths for future investigation and development to improve helicopter communications. The primary focus is on external communications to other helicopters and to ground stations.

2.0 INTRODUCTION

The overall mission effectiveness of the new Army helicopters and aircraft/aviator survivability depend on the operational performance of the communications system. Today's tactical helicopters employ sophisticated and complex computer-based integrated avionics subsystems. The entire battlefield is undergoing "digitization" and digital data are required for the avionics displays. Imagery is very important for military aircraft operations. This is especially true for low-level flight in total darkness in enemy territory. The navigation, flight control, fire control, IFF and other avionics equipment generate (or require) digital signals that are transferred to other (airborne or ground) stations or platforms elsewhere on the battlefield. This radio-frequency (RF) transfer of data must occur effectively, with accuracy, and with high first-attempt reliability over both short line-of-sight (LOS) paths and beyond-LOS (BLOS)extended ranges of 300 km or more.

A helicopter communications-link model has been developed, with emphasis on data communications, to predict system margin and operational range (OR). The model provides a framework for understanding how the scenario-related variables and radio system components interact with each other. The link model can be used for aircraft communications system design and to assess technical, cost and operational effectiveness trade-offs. It also can be used as a building block for communications network simulations. The model also will provide the framework for developing a basic appreciation of the many factors that affect communications while demonstrating the need for a total systems approach for helicopter communications research, development, testing and evaluation.

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2.1 Need The helicopter plays a major combat role on the battlefield as a multipurpose transportation platform, as an observation platform, and as a weapons platform. Aviation contributes to improved battle management as an integral part of the combined arms command and control team. Rapid advances in command, control and information distribution architecture (including advanced processing and computer algorithms to handle new imagery demands) provide a timely and accurate "picture" of the battlefield. These factors have placed challenging requirements on the aircraft communications system designer. The need for rapid, high-quality, high-volume digital communications that are also reliable, jam-resistant, secure and timely is an urgent priority. Satisfying these requirements are critical for supporting the conduct of war on the digitized battlefield 2000. Mission effectiveness and survivability for complex weapons systems (e.g., Apache and Comanche aircraft) depend on satisfying this communications need.

2.2 Communications System Path The helicopter provides many challenges for the RF designer in order to obtain the required communications system performance. The helicopter communications system described herein can be divided into five sections. Figure 1 shows the helicopter communications system's source-to-sink path. The *information source/sink* can be analog voice or digital (e.g., for pilot display, avionics imagery, target handovers). The *transmit and receive system* represents the helicopter radio. The *propagation path loss* can be line-of-sight (LOS) or beyond-LOS (BLOS). The BLOS path can be a diffraction path for high-band HF (15-30 MHz) or it can be near-vertical-incidence skywave (NVIS) high-angle radiation for low-band HF frequencies (2-8 MHz) (Ref 1). The propagation path is important because of the path loss and also because of signal distortion.

2.3 Link Margin A major helicopter communications problem is simply one of providing a sufficient signal-to-noise ratio (SNR) margin in the required bandwidth to achieve the required system bit-error-ratio (BER) on a tactical link. Because of the large pilot workload and the fast pace of modern warfare, it is necessary to achieve a high first-time message success of >90 percent correct word intelligibility for analog voice or 5×10^{-3} BER for digitized voice or 10^{-5} BER for data. This must be achieved with acceptable reliability >90 percent of the time.

The link margin must be optimized for a highly variable digital data communications channel. The major factors that contribute to a poor SNR and inadequate margin are: added propagation loss due to low-altitude flight profiles in irregular terrain (see Figure 2), transmitter output power and receiver system sensitivity limitations; friendly and enemy interference; helicopter blade and flight dynamics effects to include rotor blade modulation (RBM); signal security and anti-jam (AJ) requirements; dense packaging of aircraft system avionics; severe antenna constraints; RF band selection, modulation and bandwidth constraints; and simultaneous operation of several radios on the same helicopter. Also, modern military aircraft contain a very high density of computer-based mission avionics equipment that are housed in 60 to 90 percent composite airframe structures (e.g., the Apache and Comanche helicopters). The effects of this structural design on the communications system manifests itself as increased self-generated noise at the radio receiver input and electromagnetic compatibility (EMC) system problems. The result is a reduced SNR and an increased BER.

Communications reliability and availability are extremely important factors and they are a direct function of system margin. From the link margin, one learns whether the system will meet its requirements comfortably, marginally or not at all. Adequate helicopter communications system margin is needed to obtain and sustain the proper channel bit-error (BER) to support the mission. Link margin (M) is defined as the difference between the SNR (obtained) and the SNR (desired) for a circuit BER. Generally, a practical average figure for M of >10dB is used for planning purposes. The margin will vary for each of the three classical aviation links: ground-to-air, air-to-ground and air-to-air. The most robust link is the ground-to-air link because the ground station (e.g.,vehicular and fixed) produces the most effective radiated power (ERP). It is necessary to understand the type of mission the helicopter will fly and the communications needlines (and their characteristics) in order to estimate the communications margin required (Ref 7).

3.0 COMMUNICATIONS REQUIREMENTS

3.1 Range/Altitude Requirements The problem for VHF and UHF communications for aircraft flying low-level or NOE is: the lower the altitude, the more difficulty there is in maintaining a link of adequate quality due to terrain masking of the LOS path that usually exists for higher flight altitudes. Required flight altitudes vary and they depend on the level of conflict, air defense threat, battlefield location, terrain, weather and mission. Generally, it can be assumed that, in conventional-force missions on mid to high-level conflict battlefields, enemy air defenses will force helicopters to fly low to the earth when they are in or near threat envelopes of the enemy. Figure 2 shows typical range/altitude requirements for low-level, contour, and NOE flight regimes (Ref 2). It also depicts a generalized altitude envelope for helicopters versus distance from the forward line of own troops (FLOT). The altitude baseline is dependent upon ground obstacles such as trees and buildings. The assumption is made that an average tree height is about 15 meters. Tree height will vary in differing environments. In some dense jungle areas of southeast Asia, for example, the average tree height is over 70 meters. Notice also that more than one flight regime can be required for some missions and parts of the battlefield.

3.2 Analog Voice Communications Intelligibility Requirement The minimum analog voice channel audio SNR has been established to be a 12 dB signal-to-noise plus distortion ratio (SINAD). This SINAD is used to establish the radio receiver maximum sensitivity level. The audio signal at this level has a lot of noticeable background noise added to the desired signal. However, when typical Army spot report alpha-numeric messages were passed on this type of channel, the pilots achieved a >90 percent readability score. The human ear is a very good detector. The Army radio squelch is normally set for 12 dB SINAD. This gives maximum voice communications range.

3.3 Digital Communications Quality Requirements The requirements for data communications (Ref 6) quality can be expressed as the number of bits or characters that must be correctly received out of the total sent (or as a ratio). For digitized speech, a BER of $5x10^{-3}$ is sufficient; for data communications, a BER of 10^{-5} or better is required. For a given modem (e.g., type coding, interleaving and signal processing waveform) and type of signal (e.g., steady or fading) and noise, a curve of BER versus SNR (or E_b/N_o) is specified. This curve is used to establish the required SNR (in dB) to achieve the user-specified reliability and quality for a given scenario.

3.4 Operational Range Requirements (Ref 9) One important measure of a military radio is the operational range (OR) it can achieve in the tactical environment. The OR a radio can achieve depends on the operational scenario, the radio system parameter, the propagation path and signal loss and the ambient noise and interference (friendly and/or unfriendly) environment in which the receiver must operate. Neither the propagation loss nor the ambient noise are deterministic quantities. Therefore, the range of a radio system is best treated as a random variable. Also, the propagation, noise, and system performance models each have uncertainties that are best treated as random variables. Therefore, it is best to consider the odds of achieving a given range with a given radio system operating in a given terrain and noise environment. This approach permits statistical combinations of the uncertainties of the many parameters that enter into the prediction of communications system performance, including the statistical uncertainty in the model itself. One can compute the probability of successful communications, P_S as a function of range for a given scenario (radio system, terrain, noise environment and operational usage). By specifying a required probability of successful communications (P_{Sr}), the OR of the radio channel is defined as the corresponding range on the p_S vs range curve. This approach is illustrated in the example of Figure 3, which depicts the OR for a VHF-FM radio with a 40-watt power amplifier on a Scout helicopter communicating with an Attack helicopter while flying NOE in the Fulda Gap area of Germany. Note that for a $P_{Sr} = 0.9$, the OR is about 6 km; whereas, for a P_{Sr} of 0.5, the OR is about 22 km. Due to pilot workload, a $P_{Sr} = 0.9$ is required for NOE and contour flight. For low-level flight, the P_{Sr} can be relaxed to 0.8. Obviously, once an OR is determined, the P_S will be higher than the P_{Sr} for all shorter ranges (i.e., better communications).

4.0 HELICOPTER COMMUNICATION SYSTEM MODEL

Figure 4 is a block diagram of a helicopter communications link, emphasizing the sources of signal loss and noise. The model should provide the systems engineer with the factors affecting helicopter communications and form the basis for realistic link budget estimates and system margin computations.

The following list of sources of degradation represents a partial catalog of the major contributors to SNR degradation. The numbers correspond to the numbered circles in the figure. Reducing the signal loss and noise is important. Note the curve in Figure 5 which shows that a 2.4 dB change in SNR can mean a difference of 10^{-3} to 10^{-5} in the BER for data.

1. ***Audio.*** The helicopter audio system is a major component of the helicopter's internal communications. The audio system consists of the microphone, headset assembly, filters, distribution panels, intercommunications electronics and security appliqués. It includes all the necessary mechanisms to properly condition the voice signal for transmitter modulation and intelligible audio reception. The major contributor of noise is acoustic. It comes from a very high internal ambient helicopter transmission, engine and weapons subsystem injecting noise into the cockpit. This acoustic noise can be controlled, to some degree, by noise-canceling microphones, special cupped earphone assemblies and sound-baffling material. It is noted that RF noise can readily enter the audio system through improper grounds and shields. At the receiver, the post-detected SNR is the output that is needed to meet the intelligibility requirement with >90 percent reliability.

2. ***Modem.*** The modem provides the signal processing (coding and interleaving algorithms) and modulation/demodulation of the signal waveform. The output of the modem provides the post-detected SINAD and/or SNR with the required BER to interface with the aircraft system (e.g., pilot, displays, navigation, fire control).

3. ***Equipment Noise.*** The noise components of the transmitted (e.g., transmitter sideband noise, high-power output device noise from the RF and/or power supply, distortion products) that are included as part of the transmitted signal.

4. ***Cable Loss.*** The length of the coaxial cable between the aircraft antenna and the radio can be grater than 50 feet (e.g., the Apache). Because of this, there is considerable loss as a function of frequency. Choosing the lowest loss cable (within practical cost and weight constraints) and locating receiver and transmitter near the antenna buys extra link margin.

5. ***Antenna.*** Antennas are a significant constraint to helicopter communications. Their gains are necessarily low because of the need for azimuthal omnidirectional coverage. It is not uncommon to have communication antennas with gains of < -6 dB. Available locations generally are restricted to the tail area, tailcone or belly. In those locations, blockage by the fuselage and tail section, plus reflections from other antennas and other aircraft structures, complicates the pattern and leads to undesirable dips or nulls in some directions. Poorly joined composite seams increase the resistivity of the aircraft skin, thereby reducing its efficiency as a ground plane. This will slightly lower the radiation efficiency and gain. At HF and low-band VHF frequencies, some thin low-conductivity composites (graphite fiber types) may be only a few skin depths in thickness. In such cases, low-angle gain can be noticeably degraded. The antenna gain at low angles is particularly important for the low-altitude A-G communications or low-altitude A-A communications.

The performance of a given antenna on a helicopter will vary by location, as well as from helicopter to helicopter for the same location. A helicopter is a complex shaped body, not a flat surface; often, the communication wavelength is comparable to the overall helicopter size (at HF) or to the size of major structural components (tail, tail rotor blade, etc.). Consequently, an antenna driven against the conducting skin can excite major portions of the entire helicopter and radiate in polarizations other than the nominal one. Again, this is especially true for HF and VHF communications. The effective ground plane is usually non-symmetrical because of the aircraft shape. On conducting composite helicopters with multiple composites, the ground surface is non-homogeneous, leading to further pattern asymmetries. At UHF and higher frequencies, a few locations, such as the belly, exist that are relatively flat and large compared to a wavelength, but the presence of other scatterers (landing gear, other antennas, hatches, and openings) causes pattern distortions.

The vertically-polarized azimuth antenna pattern, which provides gain and directivity information in the aircraft yaw axis, is most important for use in the LOS helicopter communications system model. This pattern will vary for a given aircraft and operating frequency The desired elevation angle of radiation is less than +/- 3 degrees from the aircraft pitch axis when the aircraft is flying low-level or NOE. Under these conditions the required gain and pattern are essentially the same as the yaw pattern and no

correction factor is needed to account for this small difference in elevation angle. Flight tests can be used

to verify the gain and pattern across the band (see Tupper and Hagn, 1978)

6. ***Efficiency Loss.*** Gain of the antenna varies significantly across the band (see Figure 6). The losses are the greatest at frequencies below 1/4 wave resonance (e.g., VHF-FM at 30 MHz is -6 to -10 dBi).

7. ***Conducted Noise.*** The conducted component of the system-generated noise has many paths to the receiver. The presence of high in-band conducted noise greatly affects the performance of aircraft monopole-type antennas. Careful filtering and isolation are required. Antennas that isolate the noise from the radiator (such as dipoles versus monopoles for conducted noise) are used to provide a cost-effective solution to the problem. EMI can be conducted, and sometimes radiated, to antenna feeds where it then enters the receiver along with the desired signal. Although filter pins have been added to connectors to suppress the transmission of EMI, a better practice is to adequately control it at the source, by proper enclosure shielding/source suppression techniques and by good wiring/cabling shielding practices.

8. ***Rotor-Blade Modulation (RBM).*** RBM is primarily an amplitude modulation distortion of the RF signal. It occurs at the helicopter-borne transmitter for A-A and A-G links and it occurs at the helicopter-borne receiver for A-A and G-A links. RBM has its origin in the rotating parts of the helicopter (e.g., the main rotor and/or the tail rotor) and causes the received signal level in the helicopter, or on the ground, to fluctuate at a rate related to the revolutions per minute (RPM) of the rotors. The main effect on communications is the deep nulling when the direct and blade-reflected fields add out of phase with comparable amplitudes. Figure 6 shows the measured, worst case, RBM for an Apache aircraft. The antenna was a broadband VHF-FM monopole located in the upper-tail section of the aircraft adjacent to the tail rotor. The aircraft main and tail rotor blades were positioned for minimum and maximum coupling to the antenna. Note also, the relative gain variation across the band. RBM effects are worse when the rotor is a resonant length (and hence, a more efficient scatterer) and causes the margin in signal-to-noise ratio (SNR) to become negative. The RBM principally affects the incident signal picked up by the antenna by scattering the signal, then interacts with and is rescattered from the aircraft (and ground as well, if ground is close enough as in NOE operations). The rescattered signal can then be scattered a second time from the rotors and the process repeated.

RBM will also affect co-channel interference and adjacent channel interference from other sources. To a lesser extent RBM will affect (co-site) interference from other antennas on the aircraft that are transmitting, as well as internal noise sources that are radiated or conducted, plus external p-static. The effects of RBM for a given scenario tend to be worse for digital systems than for analog voice. Digital systems require more margin to overcome RBM. The net result is that the operational range (OR) for communications for a specific link is usually greater for voice than for data.

9. ***Propagation Path Loss.*** This is the basic transmission loss that is a function of range, frequency of operation, antenna height and polarization. The Longley-Rice model, now called the ITS Irregular Terrain Model (ITM), predicts the "local median" path loss value of L_b (in dB). The model also provides a prediction of the variability of this local median with time and with location. Different models are used for other frequency bands of operation (e.g., HF, SATCOM) (Ref 5).

10. ***Multipath.*** Multipath effects due to direct and ground-reflected signals adding in and out of phase are especially a problem for helicopters flying at low-level altitudes such as nap-of-the-earth (NOE) (Ref 4,9) This consists of direct and reflected RF energy arriving at the same time that causes either constructive or destructive interference (fades) on the incoming desired signal. For small changes in range of several wavelengths, the received signal can vary about the local medial value because of multipath. Figure 7 shows an example of measured signal variations with respect to time. Variations ranging to 20 dB are not uncommon. Multipath also can result from scattered energy from objects near the receiver antenna, such as parts of the aircraft, trees, etc. When the helicopter rotors (both main and tail) are turning, the rotor blade modulation (RBM) is a particularly important type of multipath. The effects of multipath are most significant and noticeable when the helicopter mission requires communications at ranges near the LOS limits of performance. Figure 8 shows

the potential effects of a data burst error that can occur as the signal gets weaker (e.g., as the helicopter transmission path gets greater). Date signals strengths above the performance threshold will provide the desired BER; signals below the threshold will be marginal; and signals that reach into the black areas will result in lost data and an unacceptable BER (Ref 10). These curves resemble that of the RBM. The difference is that RBM is periodical and multipath follows a more random (e.g., Rayleigh) distribution. The received signal fading below the local median, owing to multipath propagation, has been described by the Rayleigh distribution Figure 9 shows system margin as a function of percentage of locations for a Rayleigh distribution. Note that increasing the system margin by 6 dB picks up about 85 percent of the locations, and an increase of 10 dB picks up 95 percent of the locations.

11. ***Adjacent Channel Interference.*** This occurs when frequency assignments are not selected properly or the radio receiver selectivity is poor (usually older receivers).

12. ***Co-channel Interference (Co-site).*** This occurs when there is not enough physical separation between radio antennas. This is a very tough requirement to meet with limited space/locations available on the aircraft, especially for data radios operating simultaneously with other frequency-hopping data radios.

13. ***Radiated and P-Static Noise.*** EMX are electromagnetic sources of interference or noise occurring in the environment and includes lightning, EMP (Electromagnetic Pulse), HIRF (High Intensity RF), RFI, EMI/EMC. EMX also includes locally-generated precipitation static (P-Static). P-Static occurs when there is tribe-electric charging of the aircraft and is directly related to the rotors turning and the aircraft dynamics. Low-altitude or NOE operations in desert or other dusty areas, or over water, vastly increases the P-Static induced by the helicopter "downwash". P-Static can also occur in high atmospheric charged environments (e.g., rain clouds). P-Static can be adequately suppressed by wick dischargers on the rotor blades, provided the wicks are properly maintained. Special surface electromagnetic coatings may be necessary. If the discharger wicks are not well maintained, or too few in number, the resultant P-Static can completely block communications. Proper aircraft design is necessary so that static charges do not build up and cause arcing.

14. ***Ambient Noise.*** This is the external ambient noise in the environment of the helicopter receiver Ambient electrical noise arises from atmospheric, cosmic, and general background noise due to remote man-made sources (power lines, switches, relays, cellular phones, citizen-band transmitters, broadcast stations, etc.) (Ref. 4).

15. ***Receiver Noise.*** The noise figure of modern radios is very good. Many receivers are operating at close to the internal noise limits of the receiver. However, data communications requires wider bandwidths for operating, and this increases the noise power with which the signal must compete.

16. ***Aircraft Radio Receiver.*** The antenna output containing the desired signal and all the noise sources goes through the cable (transmission line) to the RF front end of the receiver. It is noted that the noise figure of today's aircraft receivers is very low so that essentially no noise is added at this point. The bandwidth of the IF portion of the radio and the carrier determines the predetected carrier-to-noise ratio (CNR). The predetected CNR, at the IF output, is the point where signal margin will be determined. The signal margin established at this point is an important term used to assess how well the communications link will perform. At the IF output, the signal can be directed to either the audio section of the aviator's radio to provide a post-detected SINAD for the headset where intelligibility and quality are the determining factors or the signal passes directly to the data modem for processing.

17 AGC and Squelch The AGC and the squelch operation of the radio are important factors. Improper design of the AGC (attack and release times) and improper squelch-adjustment procedures can result in system performance degradation of many dB.

5.0 COMMUNICATION CONSTRAINTS

Every aircraft imposes constraints on the communication system. The constraints vary by type of aircraft and by mission (NOE versus high-altitude operation). The constraints arise from: (a) intrinsic features of the aircraft such as size and geometry, composite materials, skin openings, aircraft dynamics and rotor motion, (b) the aircraft's normal (design) configuration and operational requirements such as

competition with other avionics for antennas/locations, amount of internally-generated interference and noise, low observability (LO) and low radar cross-section (RCS) requirements on antennas and radios and (c) mission requirements such as NOE operation and special equipment or configuration of the aircraft.

The constraints ultimately affect a communications model of the aircraft by changing the signal and/or the noise. Some constraints are relatively stationary in time, but others are time dependent (rotor modulation of a signal, impulsive noise from a strobe light). The constraints often vary strongly with frequency, due to antenna and electronics gain and match variations and coloration of non-thermal noise. Some significant constraints are discussed below.

5.1 Composite Materials (Ref 11, 12) The use of large amounts of composite materials in modern helicopters affects communication by influencing both signal and noise. Purely dielectric composite materials such as fiberglass are unsatisfactory for military and most commercial aircraft. Composite materials are made conductive in order to tolerate lightning surges with minimal damage, provide an image plane (counter poise) for monopole and grounded half-loop antennas, provide shielding against RF, RFI, EMP, HPM and other radiation, enhance LO by shielding against RF emissions from avionics, provide a circuit reference ground and provide an electrical safety ground for equipment faults and for personnel contact with live circuits. Several types of composites are used, including pure dielectric materials incorporating metal or carbon fiber meshes or screens. Well-made conducting composite materials used in helicopters provide nearly the electrical performance of all-metal aircraft. As long as good electrical bonds are achieved, the only consequences for communications are slight degradation of antenna performance and increased noise, slightly lowering the overall SNR.

Low-impedance joints between individual sections are difficult to achieve. As manufactured, composite joint impedance frequently exceeds 10 milliohms (at DC or low frequency), normally the maximum impedance allowed by specifications for metal aircraft joints. Even if the 10 milliohms is met for conducting composite joints, the joint's RF impedance may be much greater than that of a comparable metal joint. Low-impedance attachments and bonds require more care than with metal aircraft. Many communication antennas have integral metal flanges that must be well bonded to the conducting composite skin if the skin is to serve as a low-loss image plane. Fortunately, at RF frequencies, low susceptance of the bond often compensates for poor conductance. Communication antennas are usually attached to a composite skin via both the cleaning/joining method and the bolting method. If the antenna bond impedance is excessive, antenna gain, match, and efficiency suffer, reducing the available signal.

Poorly joined high-impedance seams in composite materials result in an electromagnetic shield that has many distributed leakage paths. This increases interaction of hostile environment signals (RFI, lightning, electromagnetic pulses, high-energy radiation fields) with the avionics and increases emission of internal RF noise and signals (degrading LO), compared with a metal fuselage. For communications, the poorer shielding means greater interference with other avionics while transmitting and greater interference from other avionics while receiving.

5.2 RCS and LO Low RCS is a constraint to communications. This requirement tends to drive all antennas to be conformal. Blade, whips, and other types of antennas which protrude from the surface are undesirable. However, helicopters have limited sizes and shapes of cavities in which to house conformal antennas. This restriction is particularly severe for HF and helicopter-satellite communications, but is a lesser problem for VHF communications. Some of the design iterations for antennas on composite aircraft have led to external antennas to achieve the desired gain and pattern.

Low Observability (LO) requires low RF emissions from the aircraft as a whole and from the communications system in particular. The problems of composite materials in constraining emissions have been discussed above. The impact of LO requirements on communications means that communications will tend to use spread-spectrum or frequency-hopping techniques to minimize detection. LO may also require better pattern control in certain directions, such as above the helicopter, to minimize detection by higher-altitude electronic-detection platforms.

6.0 CONCLUSIONS

This paper covered the key factors that affect communications in tactical Army helicopters. It is

noted that the helicopter weapons system is a platform of finite extent with practical electromagnetic limits. Only a few communications antennas can be placed on or within the surface because mechanical and safety considerations dictate the available locations. Most of these antennas must be placed in less than optimum locations and the electrical characteristics are compromised. Because of this, co-site interference problems are produced among radios, navigation, radar warning, fire control and other on-board avionics. Likewise, the increased amount of avionics of all kinds plus their power supplies and conditioning requirements inevitably drives up the noise levels in and on the aircraft. There are practical size, weight, and cost limits for reducing and shielding against self-generated noise. But this noise ultimately limits performance of communications and navigation subsystems. With the introduction of the fully digitized battlefield, Army aircraft communication systems will be pushed even closer to their margin limits. As a result, tough design and cost and operational effectiveness tradeoffs will be required, and a helicopter communications system performance model of the type developed in this paper will be needed to help perform these tradeoffs.

The model developed is valid for traditional tactical communications now being used in the frequency band of 2 to 400 MHz and can be used for communications system planning. However, care must be taken in using the model since each factor affects the system in different ways. For example, noise must be viewed in the operational band of interest since it is frequency sensitive (e.g., what interferes with the system at HF does not necessarily do the same at VHF); propagation path loss takes different factors into consideration for the various bands (e.g., for BLOS communications, the propagation path loss factor is more complex since it is a function of time-of-day, frequency assigned, location and condition of the ionosphere). Helicopter communications have changed with the increase in use of aircraft composite structural materials and the advent of complex computer avionics. As such, data communications within the tactical bands are experiencing varied and inconsistent results. A review of the factors presented in the model show that things such as multipath, RBM and aircraft in-band noise can have adverse effects on data communications under certain circumstances. The margin solution for today is to accept a limited OR, use more power in the signal (to improve S); modify the aircraft with filters or use noise-canceling appliqués to suppress the noise sources to minimum acceptable levels (decrease N); or send the data message many times, in the hope that it hits the right set of circumstances to get through one time.

For operation on the fully digitized battlefield of the 21st century, the need for more data at higher data rates will drive the helicopter communications problem to new heights and force the search for new methods. The data communications throughputs are changing to very-high-quality video-on-the-move with pictures of high-definition television (HDTV) resolution. This will require throughputs of data to be over 100 Mbps which today's LOS and BLOS equipment cannot handle. Helicopter data communications for the 21st century will look to satellite communications *system* technology for the answer. Surrogate satellites, also called PSEUDOLITES, low-orbit satellites (LEOS), and many other types of signal relays should be considered since each might provide part of the solution to the movement of digital voice and data (including imagery) on the modern battlefield.

The *system* approach is stressed in the widest sense of the term. That is, the source and sink equipment, signal processing equipment, RF amplifier and low-noise front end with the antenna, helicopter structure and the communications planning and training doctrine must be considered as one system. Design difficulties in one part of the system can be offset by gains in another part of the system. The increased use of composite materials (which is a reality in all aircraft), and the requirements of low RCS and LO, must be fully appreciated in designing the communications components. There must be a willingness to tradeoff some of the requirements and change methods to solve the problem. The word *system* also implies the use of all means available to pass the data, literally, from one part of the world to another (projection Army). Data communications entries (and exits) from aircraft to the many commercial-based networks all over the world will be part of the future studies of the overall helicopter communications system. The model presented in this paper should be a useful part of such a study.

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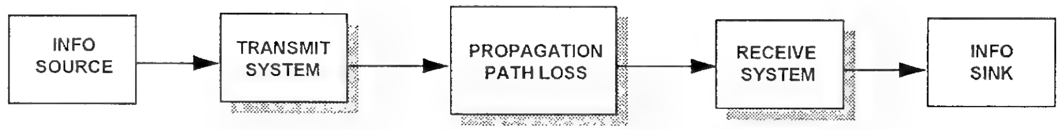


Figure 1 Helicopter Communications Source-to-Sink Path

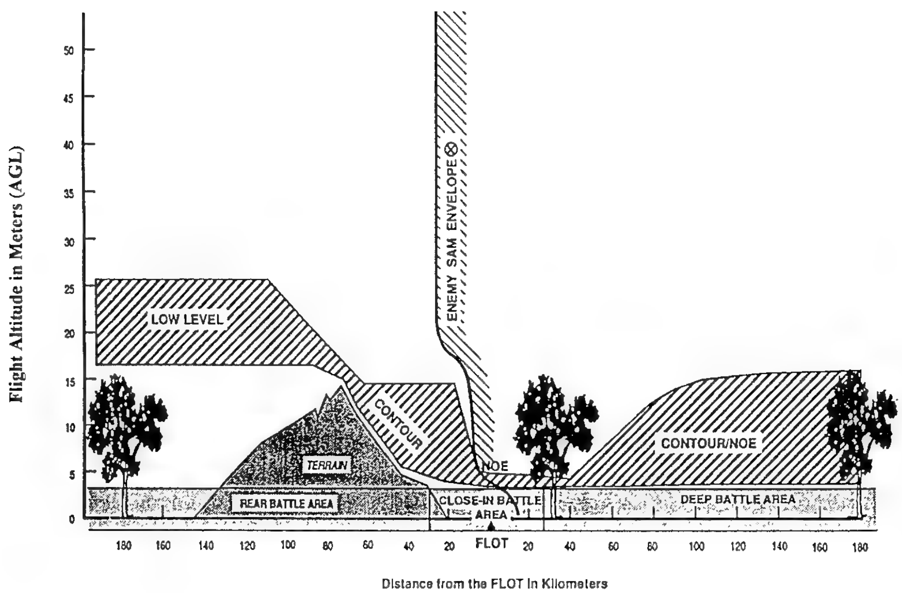


Figure 2 Battlefield Flight Altitude Estimates

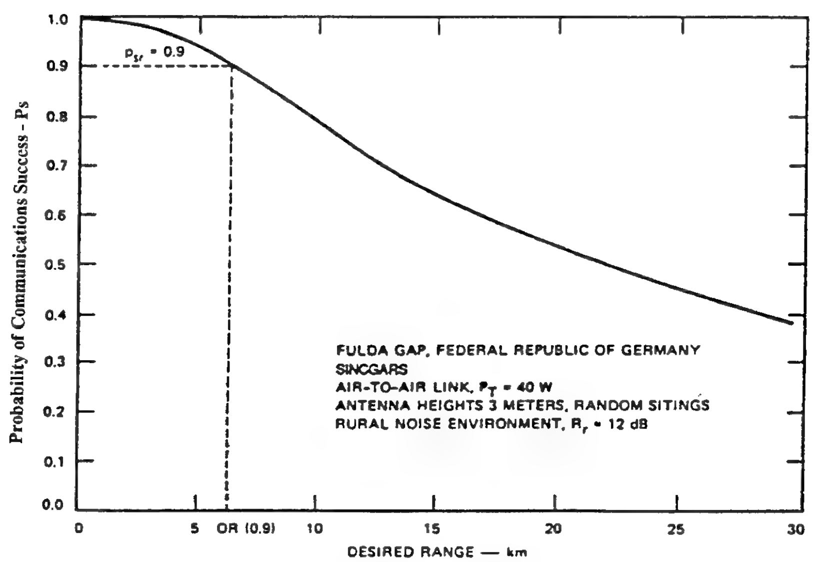


Figure 3 Example of Probability of Successful Communications (P_S) as a Function of Operational Range (OR)

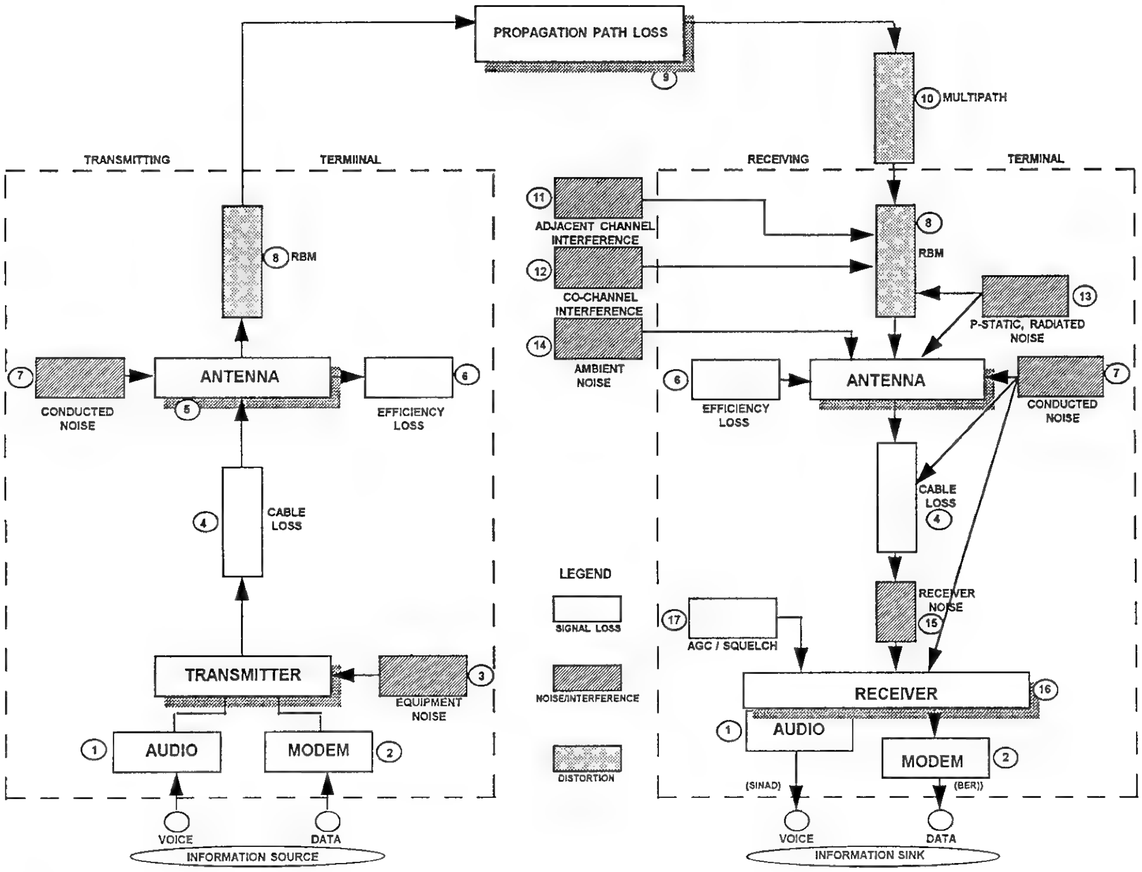
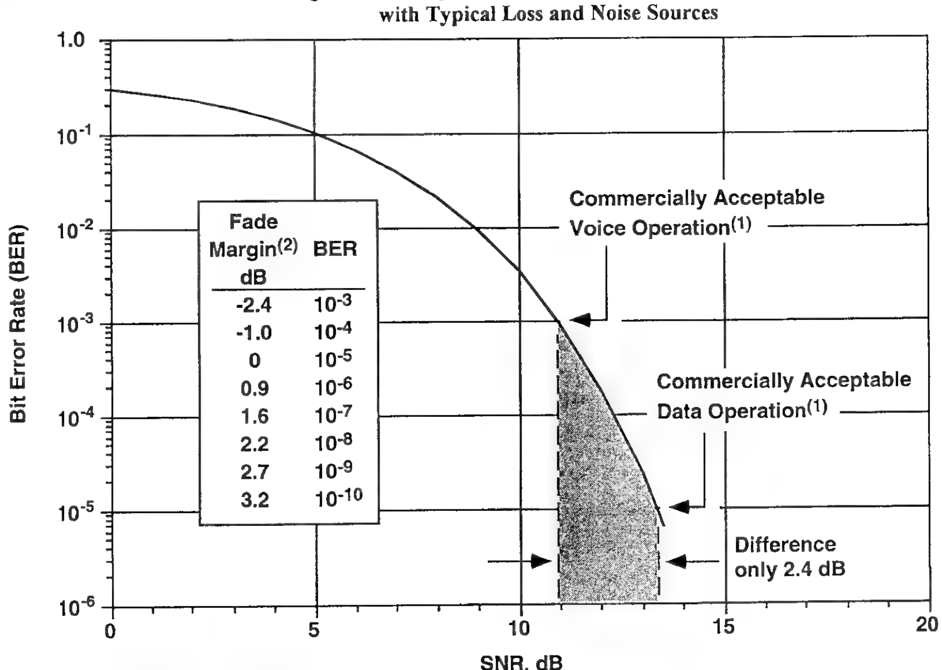


Figure 4 Helicopter Transmitter to Receiver Link with Typical Loss and Noise Sources



Notes:
1. Commercially acceptable operation is assumed to be 10^{-3} BER for digital voice mode and 10^{-5} BER for data.
2. This fade margin is in dB relative to acceptable data operation level.

Figure 5 Theoretical Non-Coherent FSK Radio Performance

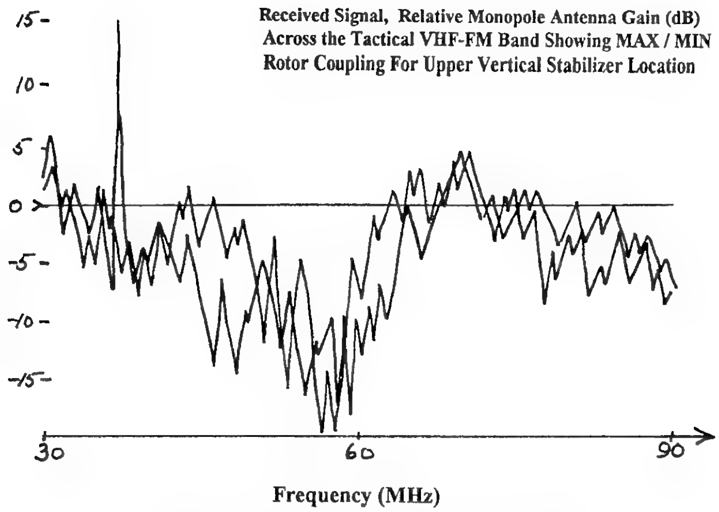


Figure 6 Rotor Blade Modulation (RBM)

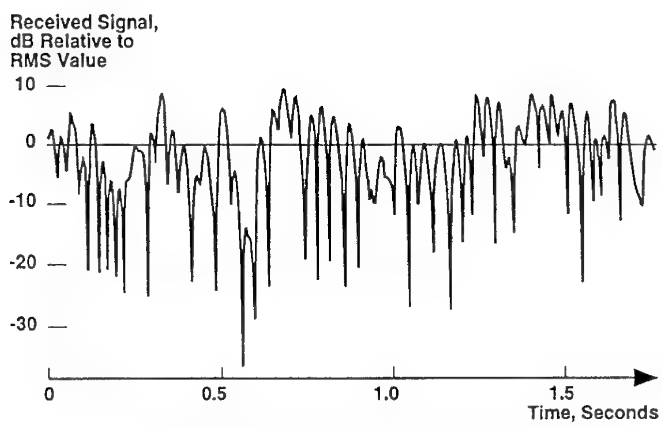


Figure 7 Multipath Signal Variation

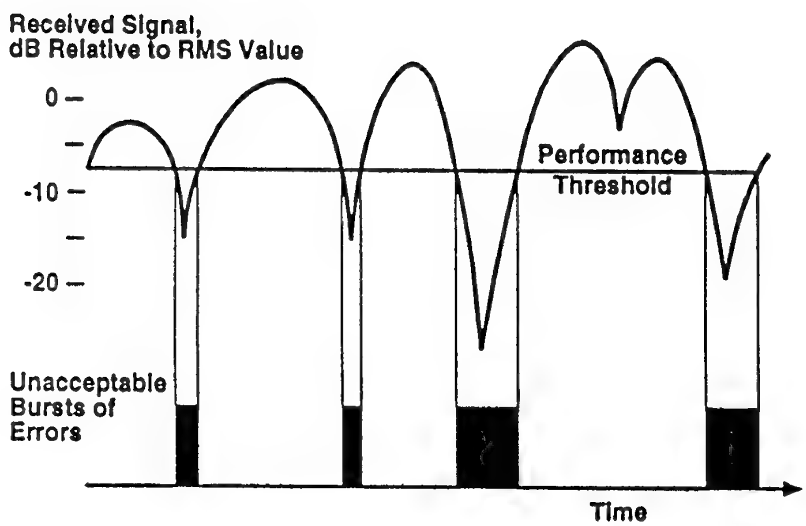


Figure 8 Error-Burst Variability

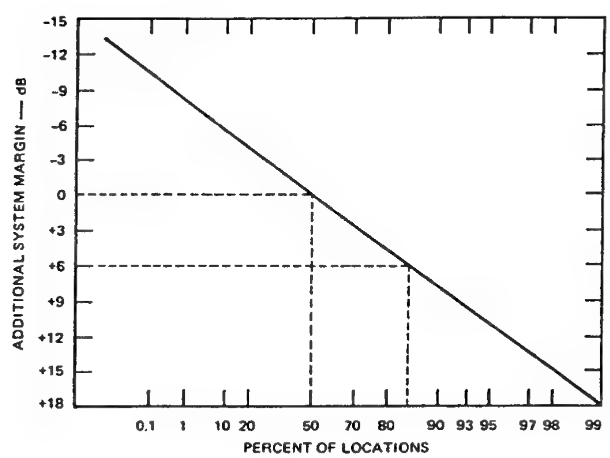


Figure 9 Rayleigh Distribution: Additional System Margin as a Function of Percentage of Locations Covered

OPTIMUM ROUTEING - ANALYTICAL CONSTRAINT OF SEARCH SPACE

W. G. Semple
British Aerospace Defence (Military Aircraft Division)
Warton Aerodrome
Preston PR4 1AX
UK

1 SUMMARY

Research into Optimum Routeing algorithms for continuous domains has generally built on the body of Discrete Search algorithms developed for routeing within networks of discrete path segments.

Unlike the discrete path problem, to which traditional continuous analysis can not be applied, the continuous problem can be approached by continuous methods, or by a mixture of continuous and discrete.

Where the cost density is continuous and differentiable, the governing equations yield geometric constraints on cost-stationary paths, giving differential equations which such paths must follow. Analysis thus reduces the need for search algorithms to generate paths branches during the search, except at singularities of the cost density. The dimensionality of the search is thus greatly reduced.

One approach is to propagate azimuth distributions of paths from the start point, and as they diverge, to populate the intervening space with disconnected path segments until the destination is approached, then to interpolate the field of path segments.

A second approach, which is also used to refine coarse estimates obtained by the first, is to relax approximately estimated optimum paths to cost-stationary in an iterative linearised scheme. In some cases, the equations are tridiagonal, enabling rapid solution.

Where the behaviour or the complexity of the cost function makes it unamenable to these methods, properties derived from the analysis can be of benefit in guiding or bounding traditional search procedures.

Initial algorithms developed and coded to date have proved the principles to be sound, and have achieved spatial search with very modest computer effort.

2 INTRODUCTION

Aircraft applications of Optimum Routeing include trajectory optimisation for fuel conservation, threat avoidance, signature reduction, sensor performance, weapon delivery, or any combination of these. In general, the path parameters, typically position and speed, are continuously variable.

Research into Optimum Routeing algorithms for continuous domains (with freedom of movement in two or more dimensions), has generally built on the body of Discrete Search algorithms developed for routeing within networks of discrete path segments – the 'road map' problem. Other methods, proposed or implemented, to address the continuous domain include Simulated Annealing and Genetic Algorithms.

Unlike the discrete path problem to which traditional continuous analysis can not be applied, the continuous problem can be approached by continuous analytic methods, or by a mixture of continuous and discrete.

On the analytical side, there appears to have been little uptake of the Pontryagin approach to trajectory optimisation [1], although successful use of this has been reported, for example by Vian *et al* [2]. Reasons may include lack of familiarity outside the Control community, the reputation of this approach for difficulty of efficient and stable solution, and the fact that the canonical forms of the equations do not always lend themselves to intuitive expression of practical routeing problems.

If we seek to solve the optimum routeing problem by classical control theory, the (usually mixed) boundary value problem in a state space will generally need more dimensions than the independent dimensionality of the problem.

Reibling [3] pointed out that if the cost density is an isotropic function of spatial coordinates only then the equation by which the path accumulates cost is the same as the equation by which a ray of light accumulates optical path length. Thus Fermat's Principle applies [4], and we can use the optical analogy to devise solution methods, or to guide deeper exploration of more complex cost regimes.

To minimise the dimensionality of the solution procedure, we would wish to solve in a space which is a subset of the state space, but which together with the track behaviour in that space (for example, its direction or curvature) is sufficient to define the track and the cost density it encounters. For example, in the two-dimensional case of the optical analogy, the states might be x, y and direction, and we would seek to solve for, say, either direction or cumulative cost, as a function of x and y only.

In the subset space, a direct attack on the differential equations will sometimes succeed, but in the general case it will fail because the solution variable, direction or cost, will be multi-valued in regions corresponding to optical interference. For practical purposes, the multi-valuedness is arbitrary; it is not like the regular $2\pi i$ value interval which occurs with more friendly multiply-connected fields.

This paper considers the application of formulae and equations obtained from the calculus of variations, as are customarily derived for Control Systems, but within an overall spatial search approach – 'ray tracing', in effect. It considers parameterisations which seek to be either intuitive or algorithm-friendly. This can lead to constructs which differ from those which would be used in classical Control Theory.

3 GENERAL CONCEPTS

3.1 The Cost-Stationary Conditions

The basic concepts will be familiar to many readers and will be reviewed only briefly here.

Two lines of approach can be distinguished. In both, we use the calculus of variations to seek conditions on cost-stationary paths which apply to all points on the path rather than to the path as a whole.

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

1) We can hypothesise global perturbation modes of a notional path, and obtain the conditions under which all such perturbation modes have zero overall cost derivative with respect to the mode weights.

   We will have a reference domain parameter to which the states and control inputs can be referred. This may be 'independent', in which case it will usually be time but could be for example fuel remaining or speed. On the other hand, it may be 'dependent', itself a function of the history, such as distance along the path.

   In either case, the destination value of the reference parameter may be fixed (specified), such as time of arrival, or not.

   We would seek to choose the perturbation modes which give convenient or efficient forms of the stationary-cost condition for trajectory optimisation.

2) We can operate directly with the derivatives of the individual state and input variables with respect to the reference variable.

   This is the conventional Control Systems approach. It usually requires that the value of the reference variable be known at both end points; this imposes a constraint on the solution techniques which may not always be necessary, at least for simplified expressions of the optimisation problem. Where the constraint is inescapable, the approach has the advantages that it is otherwise completely general in its application and that canonical expressions are available in the literature.

To demonstrate the differences in the two approaches, we will consider some simple examples.

Global Multivariate Modes vs Simple Partial Derivatives

Consider first the simplest case of travelling between two points with minimum accumulated cost, where we have a spatial cost density which is a function of position only and where there are no other boundary constraints (such as time of arrival). This is the case for which the optical analogy applies.

Denoting the spatial distribution of cost density by $\mu(\underline{r})$, and the distance along the path by s, the cost of moving from point A to point B on a path F is given by

$$cost_F = \int_F \mu(\vec{F})\, ds$$

(We might have a temporal cost density, such as rate of fuel consumption, or risk proportional to duration of exposure to threat, but we can express the time integral as a distance integral since $\mu_t = V\ \mu_s$, $ds = V\,dt$, so that $\mu_t\,dt = \mu_s\,ds$.)

We want to identify a condition on F for it to be a cost-stationary path. We consider perturbing the path by some continuous disturbance $\gamma\underline{g}(s)$ to obtain some other path G, ie $\vec{G}(s) = \vec{F}(s) + \gamma\underline{g}(s)$, so that

$$cost_G = \int_G \mu(\vec{G})\, d\sigma$$

where $\sigma(s)$ is the distance along G. If F is cost-stationary with respect to all possible perturbations $\gamma\underline{g}(s)$ we have

$$\left(\frac{d\, cost_G}{d\gamma}\right)_{\gamma=0} = \int_A^B \left(\frac{d\mu}{d\gamma} + \mu \frac{d}{d\gamma}\frac{d\sigma}{ds} \right) ds$$

If we can arrange the equation so that the elements of $\underline{g}$ become factors, then for the equation to hold for arbitrary $\underline{g}$, the coefficient of these elements must be zero everywhere.

Without loss of generality we can define $\underline{g}$ to be such that $\underline{g}(s) \perp \hat{\underline{V}}(s)$, where $\hat{\underline{V}}$ is the direction of the path F. With this definition of $\underline{g}$, it is straightforward to derive a formula for the curvature κ of a cost-stationary path:

$$\begin{aligned}\underline{\kappa} &= \text{the part of } \underline{\nabla}\ln\mu \text{ which is } \perp \underline{V} \\ &= \underline{\nabla}\ln\mu - \hat{\underline{V}}(\hat{\underline{V}}\cdot\underline{\nabla}\ln\mu) \end{aligned} \tag{1}$$

This is a particularly convenient form for path tracing.

This gives us a necessary but not of course sufficient condition for F to be *the* minimum-cost path; in general, there will be many 'local minima' – that is, paths which are cost-stationary over their entire length but which are not cost-minima over the entire domain.

In comparison, but taking only a two-dimensional example (equation (1) holds for any number of dimensions), if we proceed by defining g simply as g_x, g_y and apply the condition that F is stationary, we get

$$\mu\left(\frac{d^2y}{ds^2}\right) = \frac{\partial\mu}{\partial x}\left(\frac{dx}{ds}\right)^2 - \frac{\partial\mu}{\partial y}\left(\frac{dx}{ds}\right)\left(\frac{dy}{ds}\right)$$

and

$$\mu\left(\frac{d^2x}{ds^2}\right) = \frac{\partial\mu}{\partial y}\left(\frac{dy}{ds}\right)^2 - \frac{\partial\mu}{\partial x}\left(\frac{dy}{ds}\right)\left(\frac{dx}{ds}\right)$$

which are in effect the same equation and which are moreover the same equation as (1) above, but in a form which is suitable for some solution algorithms but which is definitely *not* as useful for other, path-tracing, types of algorithms. The equivalence is not immediately apparent, and it does not take many additional cost variables to obscure matters completely.

As a general rule, in cases where a 'natural' parameter with which to integrate cost is a cartesian 'distance' through a number of variables, irrespective of whether the reference variable is the distance itself or is only one of its component elements, more algorithm-friendly forms of the stationary-cost condition are sometimes obtained by defining the perturbation modes to be normal to those dimensions of the path which form the accumulation distance.

3.2 Some Useful Properties

If we keep our attention for the present on the very simple case of the isotropic spatial distribution – which is fitted exactly by the optical analogy – it highlights some properties which tend to be overlooked by the pure Search type of method.

Perhaps the most dramatic observation is that *a minimum-cost path will never turn away from high cost, only towards it.*

At first sight, this appears counter to common sense, but a little reflection (to add an optical metaphor to our optical analogy) shows us that it must be true. Note here that we are talking about a path with no constraints on its initial heading, and we are not considering any initial turn to attain it.

Figure 1 illustrates the effect. A minimum-cost path from A to B has basically two choices: it can go through the cost zone or it can go round it (or a compromise between the two). Which of these gives the lower cost will depend on how the much more costly is the 'cost zone' than its surroundings.

On arriving at P, many search algorithms would respond to the rising cost at P by branching left or right to avoid it, thus tracing out the path APQ. But the direct path AQ is shorter and cheaper. The search algorithm will recognise this when it eventually compares the cost of the direct path with that via P, but it should not have attempted the segment PQ. *If* the

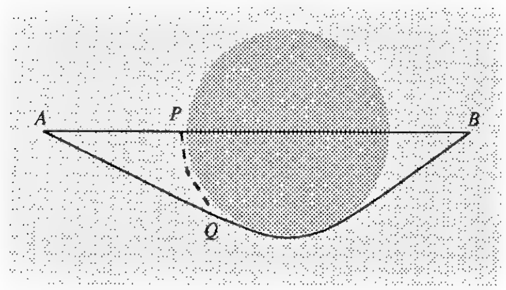


Figure 1. Path Avoiding Concentrated Threat

best path from A to B goes straight through, then it will go through P, if it does not go straight through, then it will not go through P. Either way, *it will not turn away* at P.

4 SOLUTION TECHNIQUES

The curvature-based forms of the stationary-cost condition, such as equation (1), are particularly suited to path propagation, whereas the more 'obviously' differential forms are more suited to field solution methods. Either are suited to relaxation methods.

4.1 Free Path Tracing

Basic Propagation Algorithm

In the simplest case, the two-dimensional isotropic cost distribution with the cost-stationary condition given in equation (1), we can propagate paths with very little computation.

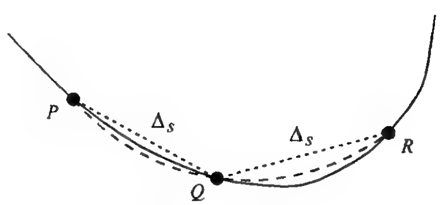


Figure 2. Circular Arc Model for Propagation

If we pass a circular arc through three consecutive nodes on a path, the curvature of the arc and the curvature of the path will be equal to the third order at the middle point, and their directions will be equal to second order (figure 2). Thus if we are given points P and Q and the curvature of the path at Q, we can locate the point R which is a given straight-line distance from Q. Given R we know the direction at Q, and hence can find the curvature from equation (1).

From what looks as if it will be an awkward set of simultaneous equations, the direction in fact drops out easily leaving a simple calculation for the coordinates of R in terms of the coordinates of P and Q and the gradient of the log cost density at Q. *No trigonometric functions are required*, and the calculations to advance the path by one step, including bilinear interpolation of $\underline{\nabla} \ln \mu$ from the surrounding grid points, requires less than 20 microseconds on a Sun Sparc IPX.

Optimum Trajectory Search

For very gently varying cost distributions, this algorithm could give a simple method of solution, by tracing an azimuth sweep of paths from the source point, selecting the (lowest cost) path which passes close to the destination, and iteratively adjusting its initial heading until the destination is hit.

That this method has little to offer in practical cases is illustrated in figure 3, which shows the wild divergence of cost-stationary tracks which have only *0.25 degrees* range in their initial headings, (swept in steps of a two-hundredth of a degree). And in the case shown here the cost densities inside the zones are only twice the background values!

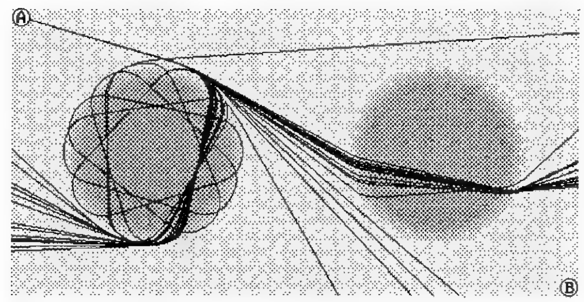


Figure 3. Path Divergence Over Two Threat Zones.

However, figure 3 does suggest a way in which it could be done. We are trying to get down towards point B. We know that when paths diverge there is an intermediate initial heading which would travel down the middle of the opening gap. So, we insert a path on the average heading in the middle of the gap. Similarly, when paths attempt to cross, we kill the path with the higher cost at the crossing. We steer the calculations by always advancing the lowest-scoring node. The score can include a heuristic estimate of the remaining cost, making it in effect an A* search. Figure 4 shows the result.

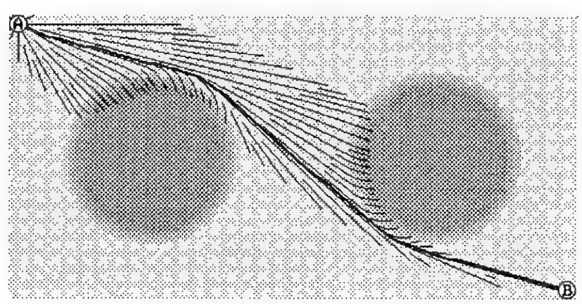


Figure 4. Path-Aligned Space-Fill Past Two Threat Zones

4.2 Grid-Aligned Tracing

When the propagated paths are free to move in space, it requires significant computational effort to keep track of whether and where they are diverging or converging. It would be convenient for the computational schemes if the path elements could always be calculated at grid points. This would in effect take our propagation-based approach and start to move back from the propagation approach towards a finite-difference solution scheme, but still retaining the essential propagation character, partly to simplify handling of the potentially multi-valued nature of the cost field and partly to retain the advantage of the filament-based approach in enabling 'promising' paths to run ahead of the rest of the field.

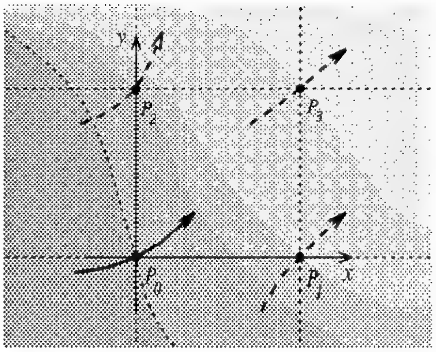


Figure 5. Grid-Aligned Space-Filling Concept

Figure 5 illustrates the concept. We can imagine a field of cost-stationary paths from a common source. Given the direction of one of these paths at point P_0, we can seek to calculate the directions at points P_1 etc, which will not in general lie on the same path.

We need to carry the value of the 'wavefront curvature' as part of the integration. We can not, as a rule, interpolate the direction between laterally adjacent nodes to obtain this, as we did with the path-aligned filling, because we will have no guarantee that the adjacent node in (x, y) is adjacent in the overall state space. That is, we fall foul of the multi-valued field problem (illustrated in a later section).

We can obtain an expression for the derivative of the wave front curvature in the path direction. Since we will on the whole be advancing in the path directions, the error resulting from the missing cross-track term does not accumulate unduly.

We obtain estimates of the path direction at succeeding nodes from one or more previous nodes. Where there is a conflict, we take the value with the lowest (estimated) cross-track error. Once again, we advance from the node with the lowest heuristically-biased score.

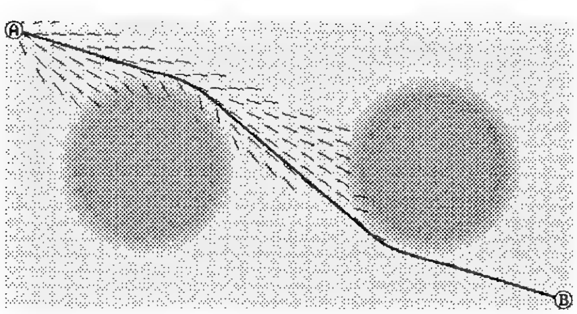


Figure 6. Grid-Aligned Space-Fill Past Two Threat Zones

Figure 6 shows the same 'double-target' geometry with the grid-aligned computed field.

4.3 Path Relaxation

Given an equation for curvature $\underline{\kappa}$ in terms of the cost gradients and the path direction, or given any other equation relating the path geometry at each point to the cost density at that point, we can construct an iterative scheme to correct errors in the geometry of the path.

An iterative scheme has been produced for the basic (optical) case which is based on the circular arc model used for the path tracing algorithm. For an n-dimensional space, it defines an error term

$$\underline{e} = \underline{\kappa} - \underline{\nabla} \ln \mu$$

and sets a linearised $(n \text{ by } n)$ correction matrix of rank $(n-1)$ for each node, for each of the influences of the changes in position of itself and its immediate neighbours, by taking the gradient of $\underline{e}$ and annihilating its $\underline{V}$ component. The indeterminacy is resolved by adding an $(n \text{ by } n)$ matrix of rank 1 which controls the segment length.

(It can be shown that, if $\mathbf{A}$ is of rank $(n-1)$ and $\mathbf{D}$ is of rank 1, and if solutions $\underline{x}$ and $\underline{y}$ exist of equations $\mathbf{A}\underline{x} = \underline{b}$ and $\mathbf{D}\underline{x} = \underline{c}$, respectively, then, subject to certain restrictions, $(\mathbf{A}+\mathbf{D})^{-1}(\underline{b}+\underline{c})$ is a solution of both equations.)

We thus obtain a tridiagonal system of $(n \text{ by } n)$ elements, which iterates very rapidly.

The algorithm has been applied to two-dimensional cases, and results are presented in section 6.

5 PROBLEMS AND ANTI-PROBLEMS

For full-blown trajectory optimisation, with full allowance for fuel usage, including the effects of turn rate and weight variation, there is no escaping the complexity of the problem and its solution will probably require a combination of complex analysis and heavy computer loading.

Even with simplifying assumptions and linearisations, some optimisation problems are less tractable than others, and some simplifications are unhelpful.

The following paragraphs indicate some of the areas which require particular attention - and also show that it is not all bad news.

5.1 Some Bad News ...

Existence

Of particular significance is fixed time-of-arrival: if we attempt to simplify the problem by assuming constant speed on a path (although allowing speed to vary with the length of the path), then the true solution (rather than the output of any particular solution technique) can be indeterminate.

As an illustration, suppose that to get from A to B we have to cross a region where threat density is high then cross an extensive region which is quite safe, travelling at a constant speed and arriving at B at a particular time. Clearly, our best plan is to go as fast as possible, to cross the danger zone as quickly as possible, then to kill time in the safe zone until the specified time has elapsed. *Where* in the safe zone we go will not matter - which means that the optimum path is indeterminate.

Where time is short and speed variable, loitering will not be a consideration, and the least-cost path will progress through the threats as rapidly as is consistent with 'reasonable' fuel usage and take the shortest route where the threat density is low. When time is comparatively plentiful, as it might be for example before a tanker rendezvous, an inappropriate optimisation procedure could have problems.

Stability

Stability is always a potential problem, although indications to date are that the 'open-loop' search approach outlined above is reasonably robust. Stability difficulties have been encountered with the grid-aligned space-fill, but is contained by

suitable formulation of the cross-track error terms and by careful handling of negative curvature of the cost front.

More serious instability has been found with the path relaxation technique. although the problems which have arisen have been those generally inherent in Newton-Raphson based methods around local minima and maxima. As a rule, the movements of nodes in any one iteration have to be limited to a maximum of, say, 2 to 8 segment lengths. The relaxation does become stable as it nears convergence.

The values in the error function relate to the gradients rather than the values of the cost density. Thus in the 'optical' case, the stationary points seen by the iterative procedure are the (log) cost inflexions rather than cost minima and maxima. This gives some rather interesting effects, especially regarding the interaction of the geometric and cost-gradient terms.

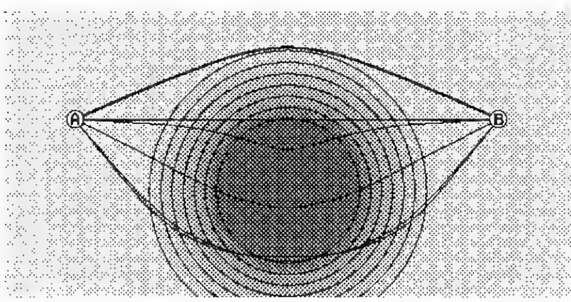


Figure 7. Unstable Relaxation Past a Single Threat

Figure 7 shows an initial straight-line estimate of the path from A to B intersecting a threat. Below the straight initial path are successive iterations of the unmodified procedure. Above the line is the correct converged path.

The initial nodes near the centre of line are subject to two conflicting influences. *All* nodes are subject to a demand to curve convex upward from their immediate cost gradient, but those in the centre see a second derivative of cost which is falling rapidly as cost rises. The linearised system thus sees a way to satisfy the equations by turning convex-up over most of the path but allowing the centre nodes to move downward to where it thinks that the cost gradient will reverse. It does reverse, eventually, but not where the algorithm expected from linear extrapolation of the second derivative!

So although the final route of the iterated path can be trapped by local channels of minimum cost density, its behaviour during the iteration process is dominated by inflexions in the density rather than stationary values.

Allowing only a small part of the second derivative into the matrices during early iterations seems to solve the problem. The exact mechanism at work remains to be investigated formally.

Multi-Valued Fields

Figures 8 shows a geometry used during the development of the algorithms to test their handling of extensive regions of interference (crossing paths, or multi-valued fields). It contains three cost zones, the first one, on the left, acting as a lens, and the pair on the right acting as a diffuser.

Figure 8(a) show simple path tracing on an azimuth sweep from point A, and demonstrates the nature of the field. Figure 8(b) shows the field path-aligned-filled under a general

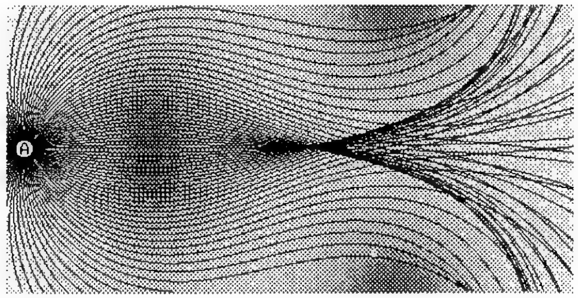


Figure 8(a). Interference Region – Crossing Paths

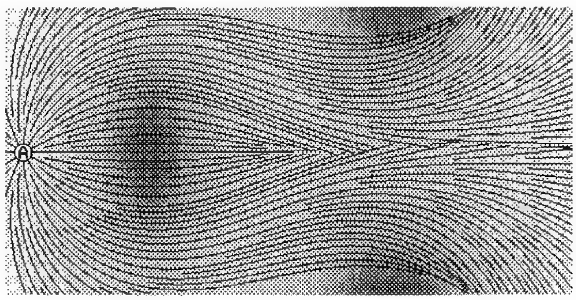


Figure 8(b). Interference Region – Path-Aligned Fill

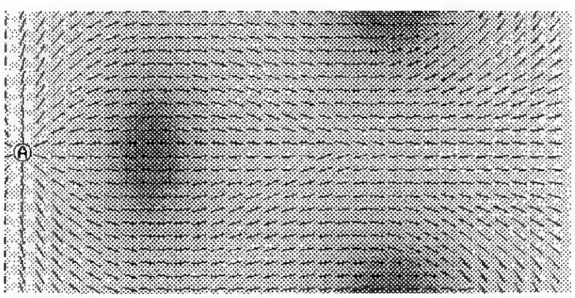


Figure 8(c). Interference Region – Grid-Aligned Fill

to 'head to the right', while figure 8(c) shows the grid-aligned response to the same directive.

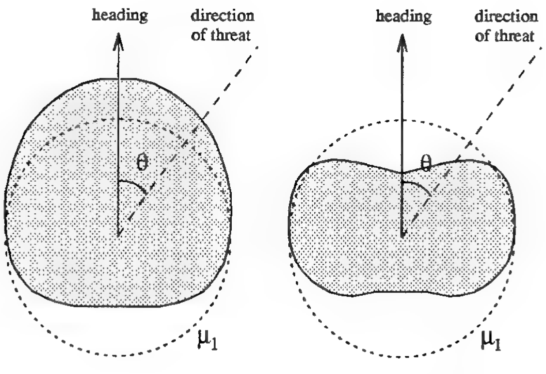
This case illustrates fairly graphically the reason why the grid-aligned algorithm can not indulge in lateral interpolation of the wavefront curvature. In the interference region, the curvature at any point has values from negative infinity to positive infinity simultaneously, and the equation in wavefront curvature has to be handled with some care. Figure 8(c) also illustrates that, fortunately, it can be handled!

5.2 ... and Some Good News

We should not always be discouraged by apparent complications. Although sometimes these will be the complications that they seem, sometimes they may be simplifications in disguise.

Non-Isotropy

For example, suppose we have a threat which is radially symmetric with respect to its source and which has a polar distribution in its angle off own heading as illustrated in figure 9(a), and suppose that this polarity can be approximated with



9(a) 9(b)

Figure 9. Polar Cost Distributions

sufficient accuracy by

$$\mu = \mu_1(r) + \mu_2(r)\cos\theta$$

where $\underline{r}$ is the position vector from the source of the threat and θ is the angle between $\underline{r}$ and our heading. We then have

$$cost_{AB} = \int_A^B \mu_1(r)\,ds + \int_A^B \mu_2(r)\,\underline{\hat{r}}\cdot\underline{ds}$$

But $\underline{\nabla}\times(\mu_2(r)\underline{\hat{r}})$ is identically zero for any $\mu_2(r)$, so that the second integral, the contribution of the non-isotropic part of the cost function, is a function of the end points only and is independent of the path. Thus in this case, the non-isotropic part of the cost function *can be omitted entirely from the calculations*.

Unfortunately, this is not always the case; it does not work, for example, with the cost polar given in figure 9(b). It does however illustrate the extent of the simplifications which can often be achieved.

Discontinuities

In many practical problems, some parts of the cost distribution will be fairly 'sharp edged'; that is, the density will change significantly over a distance which is 'small' compared with the size of the search domain, and will not lend itself efficiently to an approach based on numerical derivatives and numerical integration.

Where there are discontinuities in the cost density, limiting analysis confirms the optical analogy by delivering Snell's formula for the change in path direction at the edge in terms of the angles of incidence and refraction:

$$\frac{\sin\lambda_1}{\mu_2} = \frac{\sin\lambda_2}{\mu_1}$$

So in such cases, we can replace the continuous (but abrupt) distribution with an approximating discrete boundary, and use the relevant formulae (eg. Snell's law in the basic case) to steer the path. Thus a region which might be tackled by compute-intensive grid refinement can be tackled by (one or more) edge treatments, with a corresponding reduction in computer load.

Equivalent formulae can be derived for other cost functions.

Reversibility and Reuse

Where possible, we would wish to run the router not from start to finish but from finish to start. First, we will seldom be facing along the path when it is computed – we will have to turn on to it, and that will change the start point. Secondly, we will be dislodged from our path from time to time – pop-up threats, unforeseen obstructions, etc. If we calculate from the finish, by either of the path tracing methods, most if not all the work will have been done to allow us to extract a path from our new start position – we simply latch onto the nearest node in the traced network.

Of course, not all costs are reversible. Fuel will be, unless the start and end points are at significantly different speeds or heights. Strictly, SAM threat costs will not be reversible, because they will be functions of the times in and out of detection and tracking, then of missile range, range rate and aspect angle. However, to a first order of approximation, we can reasonable regard them as reversible. A first-order approach to optimum routeing is simply to stay out of range or out of sight, and to charge the routeing algorithm when these conditions are not met. That cost will be the same in whichever direction the path is travelled.

Thus paths will tend to be at least *approximately* reversible, and irreversible costs can be included in an iterative refinement.

Where this procedure gives an acceptable result, the full search need only be done occasionally, to respond to gross digressions or to changing circumstances, and the path can be refined iteratively at a faster rate, perhaps 0.25 Hz to 0.50 Hz.

5.3 Boundary Conditions and Waypoints

If we confine the dimensions of the search space to a sufficient set of independent variables only, treating other variables on which the cost depends as dependent, it may be at the expense of increasing the order of the equations we will have to solve, which may in turn have an impact on how we must treat intermediate waypoints.

For example, if the cost includes a charge reflecting the increase in induced drag and therefore in fuel usage due to path curvature, which will be proportional to the square of the curvature, we get

$$(\mu - 3\nu\kappa^2)\underline{\kappa} - 2\nu\underline{\hat{V}}\times(\underline{\hat{V}}\times\frac{d^2\underline{\kappa}}{ds^2}) = \underline{\nabla}\ln\mu - \underline{\hat{V}}(\underline{\hat{V}}\cdot\underline{\nabla}\ln\mu) \qquad (2)$$

where μ is the cost density with zero turn rate and ν is the increment in cost density per curvature-squared. We now have a second order differential equation in κ where before we had a simple formula.

We also get the condition that the curvature at the end points must be zero. Thus in this case, if the optimum path from A to B goes through an intermediate point P, it will in general *not* be the best path from A to P or from P to B, and conversely the best path from A to P and the best path from P to B will not, in general, define the best path from A to B given the constraint that it must pass through P.

To follow the dotted line throughout requires turning a corner at P. The corner is the limiting case of increasing curvature over decreasing distance, the product of curvature and distance remaining constant and equal to the angle turned. But the *charge* is for $\kappa^2\Delta s$, and if $\kappa\Delta s$ is finite then $\kappa^2\Delta s$ is infinite. So it is not a minimum-cost route!

The routeing here is analogous to the deflection of a loaded beam, and is illustrated in figure 10. In the first case, the beam is supported at A and B, and happens to deflect to P.

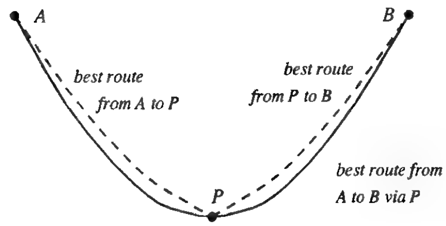


Figure 10. Intermediate Waypoint with Curvature Cost

In the second case, the beam is cut at P and the cut ends are supported there; the curvature at P is now zero and the deflections are reduced.

5.4 Fuel

The following discussion illustrates the effect of introducing fuel costs, but it also illustrates the effect of selecting the explicit and implicit state variables and the selection of the notional perturbation modes.

For simplicity, we will consider here no other cost source except fuel, and the requirement is only to cover a given horizontal distance and finish at a given height and speed with minimum fuel usage; we can fly a straight track and the time of arrival is immaterial.

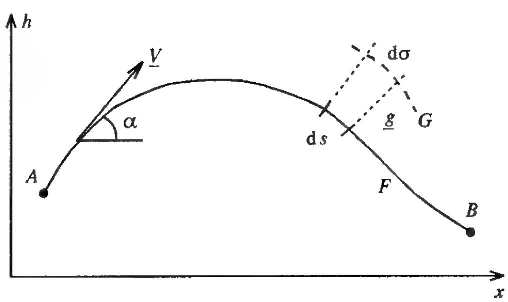


Figure 11. Range Fuel Optimisation Profile

We can reasonably assume that if we are trying to conserve fuel, we will not be making numerous violent manoeuvres in the vertical plane. We will therefore ignore the effect of curvature in the vertical plane on fuel consumption. Comparison of equations (1) and (2) show that this simplification is well worth making whenever it can be justified! In fact, it is necessary also for its waypoint properties, as we shall see.

Define:

x, h	range and height
s, σ	distances on F and G
a, α	linear acceleration and climb angle
a_0	acceleration due to gravity
κ	curvature, anticlockwise positive
$\underline{V}$	velocity vector
μ, m	fuel per distance and fuel used
$\gamma \underline{g}(s)$	displacement normal to F to reach G
g_n, g_V	$\lvert \underline{g} \rvert$ and the V change from F to G

We know the required end value of x, which suggests using x as our reference variable. However, the 'natural' variable for the calculations is either distance or time, and in this case distance is slightly more convenient. We can therefore work in s, even though we do not know the value s_B.

Our search subspace will be formed of x, h, V, m only. $\sin\alpha$ and a will be treated as dependent variables of the search space (they are defined by the search variables plus their history).

For path perturbation to derive the stationary-cost condition, we need only one geometric variable. We can not use x, since where the path is horizontal this will not enable us to span the search space. We can use h (because we do not expect to fly vertically), but it turns out that we get a convenient result for path propagation more easily using $\underline{g}$ normal to $\vec{F}$, as previously, even though in this case we do not require the 360° freedom of movement that it gives.

The stationary-cost condition is

$$\left(\frac{\mathrm{d}}{\mathrm{d}\gamma} m_B\right)_{\gamma=0} = 0$$

where

$$\left(\frac{\mathrm{d}}{\mathrm{d}\gamma} m_B\right) = \int_A^B \left(\frac{\mathrm{d}\mu}{\mathrm{d}\gamma} + \mu \frac{\mathrm{d}}{\mathrm{d}\gamma}\frac{\mathrm{d}\sigma}{\mathrm{d}s}\right) \mathrm{d}s$$

The geometry and the physics give us (simplified, and neglecting here the effect on induced drag of the interaction between m and variation in $\cos\alpha$)

$$\frac{\mathrm{d}\mu}{\mathrm{d}\gamma} = \frac{\partial\mu}{\partial V}\frac{\mathrm{d}V}{\mathrm{d}\gamma} + \frac{\partial\mu}{\partial h}\frac{\mathrm{d}h}{\mathrm{d}\gamma} + \frac{\partial\mu}{\partial a}\left(\frac{\mathrm{d}a}{\mathrm{d}\gamma} + a_0 \frac{\mathrm{d}\sin\alpha}{\mathrm{d}\gamma}\right) + \frac{\partial\mu}{\partial m}\frac{\mathrm{d}m}{\mathrm{d}\gamma}$$

so the stationary-cost condition becomes

$$\int_A^B (\phi(s) + \Phi(s))\, \mathrm{d}s = 0$$

where

$$\phi = \mu \frac{\mathrm{d}}{\mathrm{d}\gamma}\frac{\mathrm{d}\sigma}{\mathrm{d}s} + \frac{\partial\mu}{\partial V}\frac{\mathrm{d}V}{\mathrm{d}\gamma} + \frac{\partial\mu}{\partial h}\frac{\mathrm{d}h}{\mathrm{d}\gamma} + \frac{\partial\mu}{\partial a}\left(\frac{\mathrm{d}a}{\mathrm{d}\gamma} + a_0 \frac{\mathrm{d}\sin\alpha}{\mathrm{d}\gamma}\right)$$

and

$$\Phi = \frac{\partial\mu}{\partial m}\frac{\mathrm{d}m}{\mathrm{d}\gamma}$$

Our chosen form of $\underline{g}$ gives $\frac{\mathrm{d}}{\mathrm{d}\gamma}\frac{\mathrm{d}\sigma}{\mathrm{d}s} = -\underline{\kappa}\cdot\underline{g}$, and we can write the derivatives of a and $\sin\alpha$ in terms of the derivatives of V and h and $\frac{\mathrm{d}}{\mathrm{d}\gamma}\frac{\mathrm{d}\sigma}{\mathrm{d}s}$, so we can obtain an expression for ϕ in terms of g_n and g_V (using integration by parts to replace the s-derivatives of g_n and g_V by their values).

Unfortunately, we can not do the same with Φ, because $\frac{\mathrm{d}m}{\mathrm{d}\gamma}$ depends on the whole history up to P. We get the alarming looking recursive integral

$$\int_A^B \left(\phi(s) + \int_A^s \left(\phi(s) + \int_A^{s_2} (\phi(s) + \ldots)\, \mathrm{d}s_3\right) \mathrm{d}s_2\right) \mathrm{d}s = 0$$

We could evade the issue by inverting the problem, making m rather than s or x the reference variable, making x the 'cost', and seeking the path with *maximum* cost; but the algebra gets messy, and it is not be problem we are wanting to solve. (Note that if it *is* the problems we want to solve – that is, "how far can I go with a given amount of fuel?" – then using m as reference variable may be the best approach to take.)

But there is no real problem. Because there is no explicit charge for changes in direction within our search space, if our path F is the optimum path from A to B, then it is also the optimum path from A to any point P on F. We have already

established that, by definition, Φ is zero at the terminus of a stationary-cost path. So if any P on F is a valid terminus, then $\Phi(s)$ is zero everywhere. So we can forget all about it.

Substituting the expansions for the various terms in ϕ, and setting the coefficients of g_n and g_V to zero, we get

$$\frac{\partial\mu}{\partial V} = \frac{\mathrm{d}}{\mathrm{d}s}\frac{\partial\mu}{\partial a} \tag{3a}$$

and

$$\left(\mu - \frac{\partial\mu}{\partial a}\left(a + a_0\frac{\mathrm{d}h}{\mathrm{d}s}\right)\right)\underline{\kappa} = \underline{\nabla}\mu - a_0\frac{1}{V}\frac{\partial\mu}{\partial V}\underline{\hat{h}} \tag{3b}$$

which is very reasonable form for a propagation or search-based method. $\frac{\mathrm{d}}{\mathrm{d}s}\frac{\partial\mu}{\partial a}$ will vary only slowly and will be quite adequately obtained by backward-differencing.

6 EXAMPLES

This section shows examples obtained using the current two-dimensional prototype code. The examples given here are intended to be more representative of 'real' cases than the 'academic' development examples given eg. in figure 8.

All the following examples were run in *C* on a Sun Sparc IPX computer. Note that *C* forces the use of double precision arithmetic throughout, whether it is required or not, and this is reflected in the times quoted below.

In all cases, the data shown is on a 512 by 256 grid. The interpolation coefficients were precalculated and held as part of the cost grid tables; these calculations were not included in the algorithm times given below.

A consistent step size equal to 2 grid squares has been used throughout for the path-aligned filling, and a subset grid of 256 by 128 has been used for grid-aligned filling; that is, every second grid point in the original data grid was used for the propagation grid. Thus, apart from diagonal movement across the grid, the 'step' size used in the grid-aligned example is the same as in the path-aligned example.

Typically, this number of computation points is expected to be sufficient for an area of about 200Km by 100Km, although this will vary with the complexity and granularity of the cost data.

It should be noted also that the code used in following examples does not yet have any provision for adjusting the step or grid size to the scale of the cost variations. Such an adjustment would give a substantial reduction in computing time if there were significant areas of slowly-varying cost density (as would be the case in a real long-range mission).

The figures given for path cost were obtained by simple block integration of linearly interpolated data. Therefore, no significance should be seen in occasional fluctuations in the less significant digits during later iterations.

6.1 Synthetic Threat Data

Figure 12(a) shows a synthetic threat map generated to test the performance of the algorithms. The data is not 'friendly' to numerical procedures, with slab-sided threat distributions rather than distributions with smoothly varying derivatives.

The ratio of maximum to minimum cost density is 5 to 1, the base value corresponding to a fuel charge in the absence of threat and/or a residual threat estimate in the absence of specific data.

Both the space-filling algorithms are awaiting a good back-tracing algorithm, and a rough-and-ready back-tracing was used in these trials. The iterative procedure was used to correct the resulting path in each case.

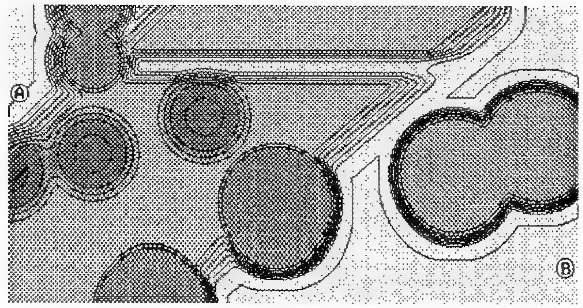


Figure 12(a). Representative Threat Map

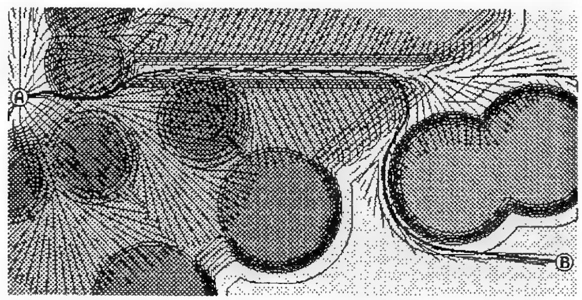


Figure 12(b). Path-Aligned Space Filling

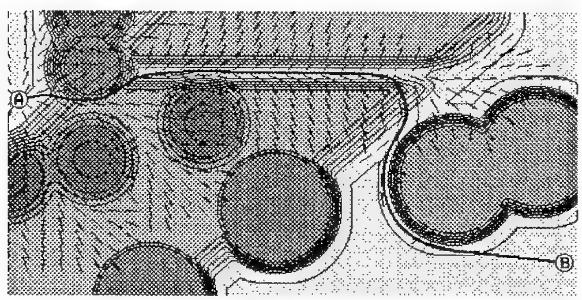


Figure 12(d). Grid-Aligned Space Filling

Figure 12(b) shows the path-aligned fill, its output path from A (top left) to B (bottom right), and the iterated path, the thicker line.

The path-aligned fill algorithm took 0.44 seconds on the IPX. It created 7062 nodes, and the priority queue had a maximum length of 143.

The output path had 307 segments; this was redistributed to 300 segments for iteration, to give an exact comparison of the iterated outputs from the two search methods. The initial cost was 1127 units. With the contribution of the second derivatives halved for the first iteration, the first three iterations took the cost to 1115, 1101, 1100, where it remained, bar a decaying oscillation in the decimal places with no visible movement of the path, during subsequent exhaustive iterations.

Each iteration took 0.026 seconds.

Figure 12(c) shows the grid-aligned fill, its output path from A to B, and the iterated path, the thicker line.

The grid-aligned fill algorithm took 1.41 seconds on the IPX. The priority queue had a maximum length of 789.

The output path had 333 segments; again, this was redistributed to 300 segments for iteration, for comparison of the two methods. The initial cost was 1105 units. The first two iterations took this to 1101 then 1100, where it remained, as before, fluctuating in the decimal places.

Again, each iteration took 0.026 seconds.

6.2 Real Terrain Height as Cost

Figure 13(a) shows an elevation map of part of the Cumbrian Mountains, an area close to BAe Warton and frequently used by RAF Tornados for training flights. The section shown is a 512×256 tile of a 100m DTED grid, the tile thus covering approximately 50Km by 25Km.

The raw DTED is used here as a test distribution of cost density. In the case shown, we are flying from the point marked *A* in the Western foothills to point *B* near the NE corner (near the NE end of Mardale).

In this example, the procedure does not attempt to provide terrain clearance height – it is a 'flat' flight in which the terrain height is used only as an intensely irregular cost distribution. The requirement is thus to stay as low as possible (on the map) and at the same time to take as short a path as possible.

The nature of the terrain makes this in some ways a more demanding test of the numerical procedure than a 'real case', where the terrain elevation would mask threat density distributions rather then be a cost distribution in its own right.

The minimum and maximum heights are (approximately) 60 metres and 980 metres respectively; a nominal average 'fuel rate' equivalent to about 130 metres has been added.

Figure 13(b) shows the results of a space-filled path trace with a step length of 200 metres and a typical lateral spacing of from ½Km to 1Km (for less 'microstructured' terrain a coarser step would be used). The geometry of the case limited the ability of the priority queue to reduce the number of steps, and 6340 nodes were calculated, 5976 of these by propagation steps, the rest by interpolation. The maximum length of the priority queue was 57.

It is noticeable that in this case the A*-style bias of the wavefront costs has done little to help the search process, because all paths are encountering cost densities greatly in excess of the minimum density which is used by the A* heuristic.

The case took 0.37 seconds to run on the IPX.

As mentioned above, the back-trace algorithm was rather primitive, operating on a network which, like the trace grid, did not adjust its granularity in the more 'geometrically intensive' regions. For example, about 9Km from its destination, the path shown in figure 13(b) misses the very narrow col of Nan Bield Pass and instead passes over a shoulder about 50 metres higher and 600m to starboard. On the subsequent 9Km to the destination it flies to the SE of the Mardale valley floor, a few metres up the hillside.

A better estimate would certainly be obtained merely by refining the back-trace code, but we also wanted to exercise and develop the iterative technique, so the iterative relaxation technique was again applied to refine the solution.

The output path had 214 segments; again this was redistributed to 300 segments for iteration, to give an exact comparison of the iterated outputs from the two search methods.

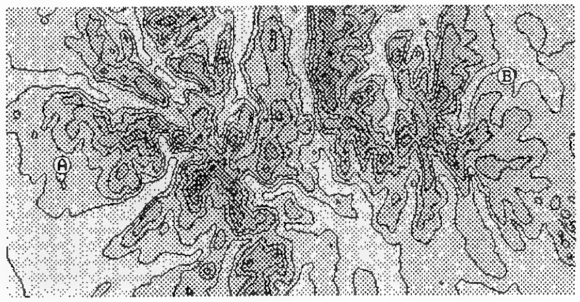


Figure 13(a). Representative Terrain

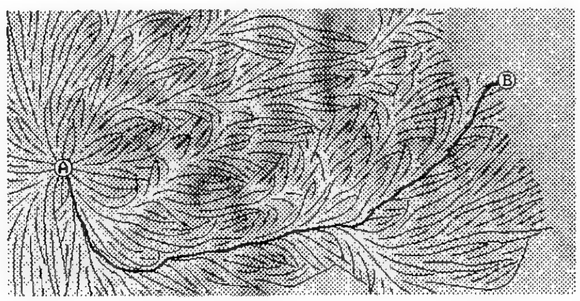


Figure 13(b). Path-Aligned Space Filling

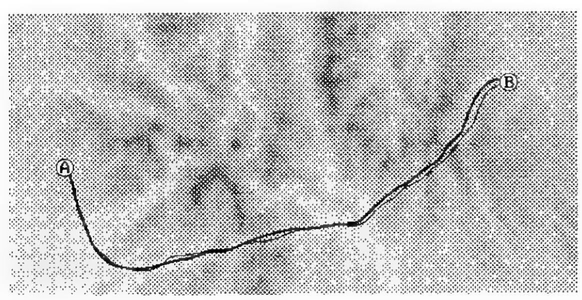


Figure 13(c). Iterative Correction

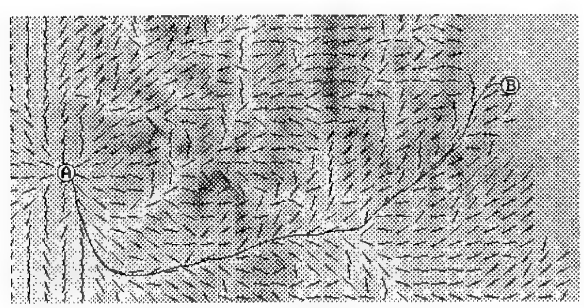


Figure 13(d). Grid-Aligned Space Filling

It was found necessary with this data to factor the second derivatives downward for the first three iterations, and the successive factors were 0.125, 0.25, 0.50. The initial cost was 1161 units. The first four iterations reduced this to 1093, and the next two reduced it to 1091, where it remained.

As with the synthetic case, each iteration with 300 segments took 0.026 seconds.

The path was also iterated with 200 segments. The plotted results were indistinguishable, but the cycle time fell to 0.017 seconds.

Figure 13(c) compares the initial (thin) and final (thick) paths. The route now goes through Nan Bield Pass, and stays lower in Mardale, but otherwise there is little significant change.

For comparison, the results of the grid-aligned filling algorithm, using a grid size equal to the step size used above, are given in figure 13(d). The figure shows 'filings' representing the path direction field at regular intervals in x and y, and the back-traced path.

It will be seen that the path is almost indistinguishable from that obtained before, but the grid-aligned method required 2.17 seconds on the IPX compared with 0.37 seconds for the path-aligned tracing. A significant factor is that the priority queue at one point contained 399 nodes, compared with 57 for the path-aligned code.

It will be noticed that the heuristic-biased wavefront on completion has more of less the same shape as with the path-aligned tracing.

7 CONCLUSION

7.1 Results to Date

Algorithms are being developed for route optimisation using the geometric constraints imposed on route geometry by zero-gradient conditions on route costs.

Two related techniques are under consideration. The first takes a spatial search approach using the geometric constraints to guide the search. The second uses the errors in the constraint equations on a given path to derive an iterative correction.

The first technique itself divides into free, or path-aligned propagation, and bound, or grid-aligned propagation. The former enables removal of many terms in the equations, the latter removes the need for complex geometric housekeeping.

To date, the techniques have been coded for two-dimensional scalar isotropic cost functions. Work is in hand to progress this to non-isotropic and multi-dimensional cases, especially to cater for representative threat tracking and missile characteristics and for fuel consumption.

Results from the code produced so far are extremely encouraging. The principles have been shown to be sound, and full spatial search achieved without combinatorial explosion of computing demand. Fine-grain searches of sizable grids have been completed in less than half a second on a workstation of modest performance. 'Real' cases will in general require dynamic cost density and derivative calculations. Conventional methods can deliver these at sufficient granularity and at a sufficient rate for the present search methods, given that there appears to be scope for the average granularity in the method to be coarsened considerably.

For refinement of coarse-grained search output, a fast iterative scheme has been produced. Subsequent development will address extending its stable range of usability.

7.2 Further Work

The following work remains.

Algorithms remain to be derived for many of the complex cases, and test/prototype code has to be produced for some of the existing algorithms.

Work is currently in progress to produce a more accurate back-trace mechanism and to develop suitable fuel and inter-visibility modules (both algorithms and architecture).

There is obviously scope for developing step-size adjustment in all the algorithms. This would enable automatic refinement in pathological areas, thus ensuring robustness, and automatic coarsening in benign areas, reducing the processor load and the demands on the supporting modules.

Consideration will be given to making use of the singular edge formula as an aid to supporting simpler definition of threat maps.

It is not proposed to take the theoretical effort beyond the above items until a benchmark system of representative real-plus-simulated avionics has been built, tested and evaluated. When this has been done, subsequent development of the theory will take place in parallel with development of the hardware and architecture, including flight trials.

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A TACTICAL NAVIGATION AND ROUTEING SYSTEM FOR LOW–LEVEL FLIGHT

C Hewitt and S A Broatch
GEC–Marconi Avionics Limited
Rochester
Kent
ME1 2XX
United Kingdom

SUMMARY:
Many types of offensive air operations need to be carried out at low level in order to ensure survivability and to maximise the probability of mission success. However, such a flight trajectory is workload intensive and leaves little room for pilot error. It would be highly beneficial if the activities of in–flight route planning, obstacle, threat and terrain avoidance, and time and fuel monitoring could be automated.

This paper presents an integrated solution to this automation problem based on the effective exploitation of terrain and mission databases.

The requirements of the component parts of this system are presented. These include:

a. An optimum routeing algorithm, together with the criteria used in selecting the optimum four dimensional route for all mission scenarios.

b. A ground and obstacle collision avoidance system which enables the pilot to fly low, whilst providing timely warnings of imminent high terrain and obstacles.

c. The navigation accuracy required to support the optimum routeing and collision avoidance systems.

The paper then describes a number of systems that have been developed by GEC–Marconi Avionics with the support of the Defence Research Agency (DRA), UK Ministry of Defence. The first is an optimum routeing algorithm which uses terrain and mission databases to generate an optimum route, taking account of threats, terrain, obstacles, time and fuel constraints. A description of a predictive Ground and Obstacle Collision Avoidance Technique (GOCAT) is then presented. This uses a terrain and obstacle database to assess whether the current and future aircraft trajectory is safe. Finally the navigation requirements to support these systems are discussed and a solution based on integrated INS, GPS, Map Referenced Navigation (MRN) and Edge Detection Navigation (EDN) is described.

1. INTRODUCTION

Many types of offensive air operations need to be carried out at low level in order to ensure survivability and to maximise the probability of mission success. However, such a flight trajectory is workload intensive and leaves little room for pilot error. It would be highly beneficial if the activities of in–flight route planning, obstacle, threat and terrain avoidance, and time and fuel monitoring could be automated.

This can be achieved by the integration of three major functions, namely Optimum Routeing, Ground Collision Avoidance and Precision Navigation. A database management system is required for the storage and management of the mission, threat, terrain and obstacle data required to support the above functions. Displays are also required to provide enhanced situation awareness.

2. REQUIREMENTS

2.1 Optimum Routeing

The Optimum Routeing function is required to calculate a flyable route from the aircraft's present position towards the destination. The route must pass through a set of pre–defined waypoints and must avoid significant terrain features and all known obstacles and designated no–go areas. The route should be optimised to maintain desired track and time–on–target whilst minimising exposure to threats (known and unknown), exposure to adverse weather, manoeuvre and fuel consumption.

At take off, the crew will most likely follow a route plan generated by a ground based mission planner. As the mission progresses, there are a variety of reasons why this route may no longer be suitable, for example, if additional threats are detected, or if the pilot is forced to stray a large distance off track. Under these conditions, the optimum routeing function should modify the original route plan to account for the changing situation. The crew are unlikely to want a different route displayed unless it is significantly better than the previous route. Therefore, criteria are required for comparing routes and determining whether one is significantly better than another. Only if there is a significant improvement, should the new route be offered to the crew. The crew can then either accept the new route, retain the original route, or request a modified route.

The crew, for whatever reason, may also need to modify the proposed route or use an alternative. This could be achieved by moving or deleting one or more waypoints or by introducing new waypoints. If the automatic router subsequently determines that the selected route is not viable, or is unsatisfactory, it would be necessary to provide a means of conveying this information to the crew, giving the reason why. At the same time a route must always be produced which is the best in the circumstances. The crew must never be left with a blank screen, or an error message stating 'too difficult' or 'ran out of time'.

2.2 Ground Collision Avoidance

In order to ensure survivability and mission success the pilot will have to fly as low as possible, following the trajectory calculated by the optimum routeing function. In order to avoid the risk of collision with the ground and obstacles a collision warning function is required which will allow the pilot to follow the required low level trajectory but which will generate a pull–up warning in the event of an imminent collision. This pull–up warning should occur as late as possible to avoid over exposure but there must be no missed warnings.

Trying to predict the shape of the ground from the terrain already overflown cannot account for features such as cliffs, and clearly it is impossible to predict obstacles. A terrain and obstacle database is therefore required in order to provide protection against terrain and obstacles about to be overflown.

The other requirement is an ability to calculate the aircraft flight path and the aircraft response to a pull–up manoeuvre. The

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pull–up manoeuvre should be sufficiently severe to enable the aircraft to remain close to the ground and to start climbing as late as possible, whilst still being within the capabilities of the aircraft and pilot. In fact, the best manoeuvre is probably the standard pull–up manoeuvre which is ingrained into pilots during training. (e.g. a 4g pull–up followed by a 30 degree climb out). This has two advantages, firstly the pilot will instinctively react to this type of manoeuvre and secondly the pilot will be able to relate the warning to the time and distance from the terrain/obstacle for which the warning was generated.

2.3 Precision Navigation

The Optimum Routeing and Ground Avoidance systems require accurate information relating the current position of the aircraft to the terrain and the features on it. Inertial navigation systems on their own do not provide sufficient accuracy. Satellite based navigation systems such as GPS, although highly accurate, do not give position information with respect to the terrain, and are also vulnerable to jamming and degradation due to terrain screening. The solution to this problem is to use a terrain based navigation technique, Map Referenced Navigation (MRN), integrated with other sources of navigation including INS and GPS.

2.4 Database

A number of different types of data are required to cater for the needs of various components of the system. The database manager therefore must be able to accommodate these different types and provide the required information in a timely fashion. These range from long–term, fixed data types to very short–term transient ones. The bulk of the data held in the database store, and thus controlled by the Data Base Management Systems (DBMS), is long term in nature. Map and terrain elevation data have lifetimes, i.e. the time between data updates, that can be measured in terms of years. For this type of data the DBMS only needs to keep track of where this data is held in store. It is not necessary to keep track of multiple issues of the data.

At the other end of the lifetime scale is the transient data which is updated many times during a mission. Aircraft status information, including fuel, weight, configuration, navigation information and weapon status are examples of information which will be updated frequently.

In between the two lifetime extremes lie the 'slowly transient' data types such as weather, battlefield scenario etc. which can be expected to change several times during a mission. For this data, the DBMS must be responsible for the collation of the data and ensuring that the user functions always receive the latest coherent set of information.

2.5 Displays

The displays are required to allow aircrew interaction with the routeing system and to provide situation awareness.

During route planning, either on the ground or in the air, the crew require a means of visualising the complete mission, or specific portions of it. The route, including waypoints, obstacles, known threats, no–go areas and other features taken account of by the optimum router should be shown. The crew require a means to add, delete and move waypoints.

When flying the mission the crew require a means to visualise the route, terrain, obstacles and threats immediately ahead of the aircraft. This display must be updated in real time.

3. SYSTEM DESCRIPTION

3.1 General Description

A flyable test rig, shown in Fig. 1, was developed using commercially available hardware.

The system comprises three major subsystems, namely Optimum Routeing, Ground Collision Avoidance and Precision Navigation.

The Optimum Routeing subsystem is further decomposed into the Mission Planning and Tactical Routeing functions. The mission planning function calculates a coarse route, defined by a sequence of straight line segments, for the rest of the mission. The tactical routeing function takes this coarse route and calculates the optimum flyable route, defined as a sequence of curved arcs, for the next few kilometres.

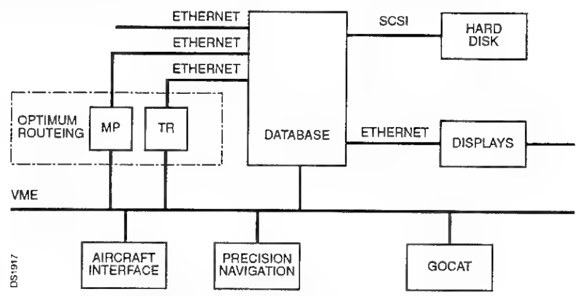

Fig. 1 System block diagram

A set of standard processor cards are used to support each of the main functions. These processors are controlled via the VME bus, but receive bulk data from the database over a set of serial interfaces. This enables an expandable architecture to be used without overloading the main VME bus. Currently these serial interfaces are implemented using standard Ethernet links, but could be replaced by faster links if necessary. Each processor card also has a RS232 interface which is used for debugging.

The database is controlled using a processor card with multiple Ethernet links to distribute the data. The actual data is held on a 1 Gbyte disc connected via a SCSI link. A hard disc has been used for demonstration purposes. For a production system solid state memory is likely to be used. The database has an additional serial link to an external computer, normally a laptop PC, which is used to download mission data to the system at the start of a flight and can be used to configure the system for different flight trials requirements.

The Displays subsystem comprises a set of specialist graphics cards with a general purpose processor acting as a controller. Communication with the rest of the system is via an Ethernet link with the database management system.

3.2 Optimum Routeing

The Optimum Routeing function comprises two processes, known as Mission Planning and Tactical Routeing.

The mission planner begins by taking a mission route from a ground based Mission Planning System (MPS) and, if necessary, refines this route during the mission. Full account is taken of the overall mission scenario and a coarse, but near optimum, four–dimensional route from the aircraft to the target is calculated. The route is chosen by taking account of the changing threat environment, sector corridors, terrain, meteorological conditions, no–go areas, and any imposed limits, for example fuel, time and performance constraints. In addition, the mission planner can take account of any constraints imposed by the on–board navigation system. For example, if MRN is being used, then routes can be

planned to pass over suitable terrain to ensure good navigation performance. The Mission Planning algorithm developed by GEC–Marconi Avionics, unlike many of the alternative algorithms available, computes mission plans within seconds, this period being largely independent of the threat density.

The tactical routeing function takes a more detailed account of factors such as aircraft performance constraints, threats, obstacles, and the terrain. The tactical router generates a route which is within the capabilities of the aircraft and dynamically acceptable to the crew, i.e. a route which is flyable.

3.2.1 Mission Planning Function

The Mission Planning Function starts with a set of waypoints, which may be entered from a ground–based mission planner, and calculates a near optimum route (comprising straight line segments) towards the target and home again. The system accounts for the changing threat environment, the terrain and any imposed limits, for example, fuel and time constraints.

A large number of potential routes are generated and each one is assigned a 'cost' value. The system then selects the route with the lowest cost.

The cost of the route is made up of several elements, including:

a. Threat cost

b. Exposure cost

c. Time cost

d. Fuel cost

In addition, the algorithm could be expanded in the future to take account of radar cross section.

The threat cost is related to the time that the aircraft can be seen by the threats. This costing takes account of terrain screening, threat ranges, threat density, relative threat lethalities and ensures that selected route has minimal exposure to known threats.

The exposure cost gives an indication of how well the aircraft will be screened from unknown threats. The value will be high in exposed areas, such as flat plains and will be low in places such as curved valleys. Therefore, this costing will tend to give a higher weighting to routes which pass through valleys and other well hidden areas.

The time costing ensures that routes are chosen which will allow the aircraft to have the correct time on target. Routes which are either too long or too short are rejected. However, the route length is allowed to change, and in these circumstances the time on target is achieved by varying the aircraft speed.

The fuel costing ensures that routes are chosen which will allow the aircraft to complete its mission with adequate fuel available for the egress phase.

A vast amount of processing time and power would be required to consider every possible route between take off and the target. The mission planning system uses random selection techniques to generate a near optimum route in a short period of time.

The system starts by taking the straight line joining the take off and target positions for the outbound route and the target and return airfield for the return route. Intermediate waypoints can also be added if required. A number of routes (typically 100) are then generated by placing a single waypoint at a random position on either side of the original track (Fig. 2). These routes are then costed and those (typically 10) with the lowest cost are retained for further modifications. The original straight route may be rejected at this stage.

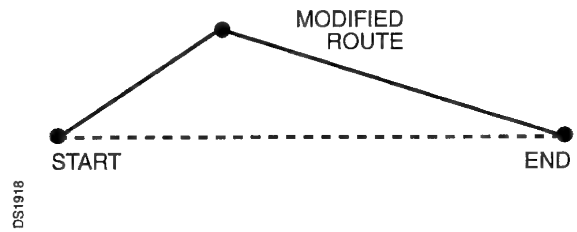

Fig. 2 Route selection during 1st stage of algorithm (first modification method – introduction of waypoint)

The second stage is to modify each of the surviving routes a number of times (typically 10). Each surviving route is modified, using one of four methods described below, and then costed. The resulting routes are then also modified and costed. This process is repeated until a number of modifications have been performed on each route. Assuming that 10 routes were each modified 10 times, then 110 routes would remain at the end of this stage – the original 10 routes, and 100 new routes.

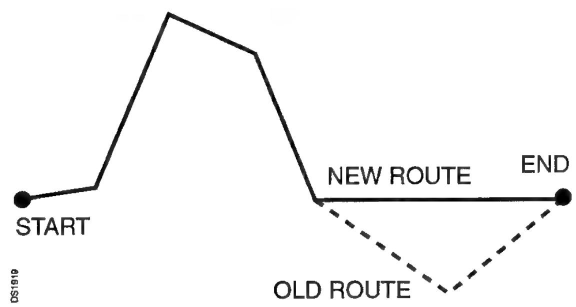

Fig. 3 Second modification method – replaces two phases by a single phase

A number of routes (typically 10) with the lowest cost are retained and the process just described is repeated. After an arbitrary number of routes have been generated (typically 1000) the route with the lowest cost is selected for use.

The methods used in the second stage are:

i) Lengthen the route by adding a waypoint (Fig. 2)

ii) Replace 2 phases of the route with a single phase (Fig. 3).

iii) Randomly select a waypoint and alter its position (Fig. 4).

iv) Take 2 adjacent phases and remove the common waypoint to leave 3 shorter phases (Fig. 5).

All four methods are chosen at random but, depending on certain factors, some are more likely to be chosen than others. For example, the first method lengthens the route, and therefore, is unlikely to be used if fuel is low.

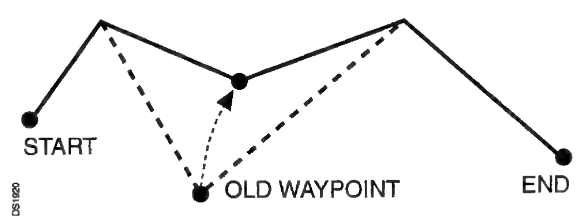

Fig. 4 Third modification method – move a waypoint

The route generated by the system is defined by a set of three dimensional waypoints, and can be supplied in a variety of forms depending on the requirement. The waypoints could be supplied to the steering system of the aircraft, or alternatively, could be provided to the pilot as an advisory route.

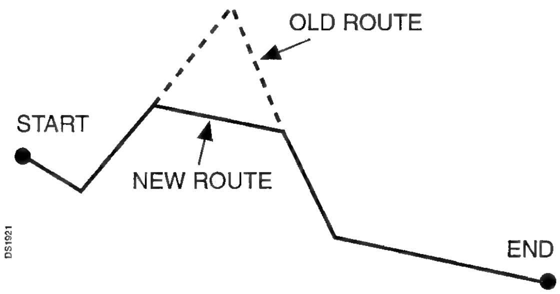

Fig. 5 Fourth modification method – cut out a waypoint

If the mission planning function is unable to find a route that meets all the mission requirements it nevertheless offers the best route for display and for input to the tactical routeing function. A diagnostic message is generated which includes an indication of the problem with the route.

The mission planning function is run continuously as a background task and compares new route that it generates with the route currently being used as the mission plan. If it deems that the new route produced is significantly better than the current route, then the mission planning function asks the aircrew whether the new route should be accepted.

3.2.2 *Tactical Routeing Function*

The tactical routeing function produces a flyable four–dimensional route from the current mission plan which still avoids all no–go areas and obstructions and minimises the amount of time spent in threat lethal zones and adverse weather. The route ensures that, if possible within the mission time and fuel constraints, the aircraft will reach each waypoint within the required time window, at the required speed and heading and within the required positional accuracy.

The tactical routeing algorithm is split into two parts. The first calculates the optimum horizontal route. This route will tend to fly around threats, high terrain and other areas to be avoided. This is constrained by taking account of costs such as distance off track, fuel usage, exposure to known and unknown threats, aircraft speed, time and the aircraft horizontal manoeuvring capabilities. The second part uses the horizontal route to generate the vertical component route.

The tactical route covers the next few kilometres and is re–calculated every second. In some circumstances the algorithm may not have been able to calculate all possibilities, but is designed to keep track of the best route found to date. If this situation is encountered the horizontal search is halted in sufficient time to ensure that the four–dimensional part of the algorithm still has time to run.

A similar methodology is used for calculating both the horizontal and four–dimensional routes.

For the horizontal route three possible route segments are calculated from the current aircraft position. These three segments are based on the current turn rate, and turns to the left and right. For each of the three new segments generated a series of checks are made to see if they are worth retaining. Segments will be rejected for a number of reasons:

- Turn rate to get to the end of the route segment would exceed aircraft capability
- Aircraft heading outside constraints
- Position too close to an obstruction
- Position lies within a no–go area
- Off track distance too large
- Route too long
- Aircraft position and heading at the point are very similar to those of a lower cost route to that point.

For each valid route the cost of getting to the end point of the route is calculated. This cost is based on the following factors:

- Distance off track
- Fuel usage
- Threat exposure
- Turn rate
- Speed and time

The costs to reach each of the three new end points are sorted into ascending order and stored in a list. As further new points are generated this list is extended and sorted producing a set of costed and sorted routes, with the lowest cost route so far found the first in the list. This process is repeated until the end of the tactical route is reached, or the available time has expired.

For the vertical algorithm current pitch and change in pitch rate are used to generate three potential vertical routes. These three routes are then checked for suitability by checking against the following rejection criteria:

- Ground clearance below a Minimum Clearance Height
- Pitch angle too high
- Pitch rate too high.

For each valid route the cost of getting to the end point of each route is calculated. For the vertical route the cost is based on the following cost factors:

- Threat exposure
- Height
- Pitch angle
- Pitch rate.

In a similar way to the horizontal algorithm the resulting routes are sorted into ascending order and stored in a list, with the lowest cost route found so far being the first in the list.

This combination of horizontal and vertical algorithms ensures that in the limited time available the lowest cost four dimensional route found is provided to the pilot.

3.3 Ground Collision Avoidance

The basic principle of the Ground and Obstacle Collision Avoidance Technique (GOCAT) is to predict the potential position of an aircraft if it carries out a hard pull up and to compare the height of the aircraft to a terrain and obstacle database. If the aircraft is in danger of flying too close to either the ground or an obstacle then a warning is generated. The warning is generated sufficiently early to allow for pilot and aircraft reaction times and to ensure a pre–set clearance margin is maintained. A key factor in the GOCAT algorithm is that the potential height of the aircraft is calculated assuming a hard pull up. This minimises the possibility of nuisance warnings as GOCAT assumes that the pilot is aware of the aircraft position with respect to terrain and

obstacles until it becomes obvious that he is not. GOCAT also uses a standard pull up response trajectory when predicting the aircraft height. By using a standard response the pilot can calibrate the implications of a warning against the required manoeuvre to avoid the potential danger. GOCAT has the ability to give advance warnings of potential dangers so that advisory caution messages can be generated. If these are ignored then further cautionary messages, ultimately followed by pull up warnings, can be generated. The cautionary messages are separated by a set time interval, with increasing urgency and severity of the warning message.

GOCAT requires only standard navigation parameters as an input and access to a terrain and obstacle database. The algorithm has been designed to model generic aircraft response manoeuvres and therefore can be used with a wide range of aircraft with no modifications. Changes are only required to specific parameters describing the individual aircraft flight characteristics such as sustainable climb angle and g capability in reaching a sustained climb angle.

3.3.1 Algorithm Description

The GOCAT algorithm is split into a number of stages which are described below.

The first step is to use the current aircraft position, altitude and velocity to predict the aircraft position when it will first respond to a pilot initiated pull up by taking account of the pilot and aircraft response times. The point in space at which the aircraft first responds to a pilot initiated pull up is called the Reference Point.

From the Reference Point the area over which the aircraft could potentially fly is determined (the search area) and a series of checks are performed in this area to determine if a warning is required. The search area comprises a set of positions, characterised by a regular grid. For each point on the grid the potential height of the aircraft is calculated, assuming that a pull up has been started at the reference point.

The manoeuvre used for calculating the height of the aircraft is a constant g manoeuvre, followed by a constant climb angle. This approach means that the algorithm is flexible and can be modified easily for fast jets or transport aircraft by changing the g level and sustainable climb angle. It also gives the pilot a constant trajectory path to reference against. For example in a fast jet the g level could be set to 4g, followed by a 30 degree sustained climb. This is typical of a standard escape manoeuvre. Therefore, if the pilot is given a pull–up warning he knows that by using a standard pull–up manoeuvre he will be safe.

The height of the aircraft at each point in the search area also takes into account the bank angle that would be required to reach that point from the reference point. The potential height that could be achieved is then reduced accordingly.

The height at each position on the grid is compared with the terrain and obstacle database. If the potential height of the aircraft is less than the terrain/obstacle height plus a clearance margin, then a warning is generated. The type of warning depends on the relative position of the grid point which is being tested and the current aircraft position. It also depends on the time before avoiding action must be taken.

The clearance margin used when calculating whether or not a warning should be generated is dependent on the system errors. As these errors change with time the clearance margin is continually re–calculated to take account of the current values of the system errors. This in turn means that an assessment of the current system error values is made continually. The key contributions to the clearance margin are the navigation errors and database errors. The significance of the database error depends on the type of navigation system used and its accuracy with respect to the terrain.

There are three categories of warning from GOCAT which are shown in Fig. 6 for an aircraft in turning flight.

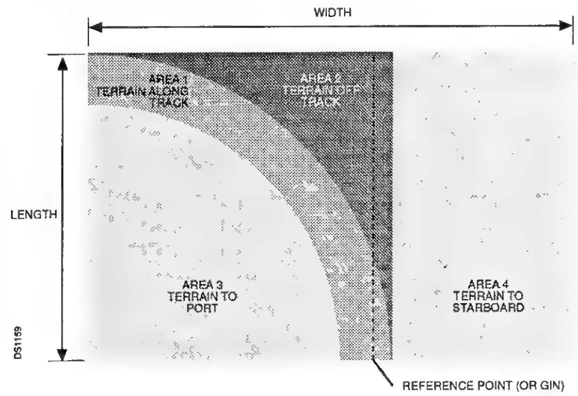

Fig. 6 GOCAT search area zones

The most important are warnings along the predicted future path of the aircraft, termed along–track warnings. along–track warnings are further broken down in a sliding scale of warnings, depending on the time taken to reach the terrain/obstacle causing the warning. Fig. 7 demonstrates the concept behind this approach. From the reference point a set of pull up curves are calculated, with each member of the set relating to a severity of warning. For example the furthest look ahead curve will give the pilot the most time to take account the warning and so is the lowest severity of warning "terrain". The number of steps in the warning cycle, and the time between the warnings is dependent on the type of aircraft.

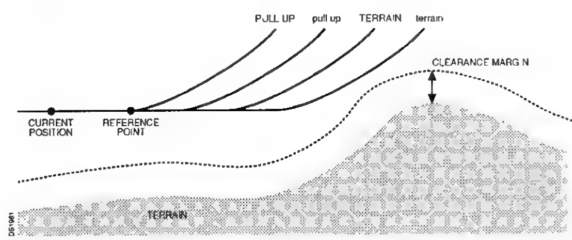

Fig. 7 Increasing urgency of GOCAT warnings

The second type of warning is only applicable in turning flight. In turning flight the normal response to a warning is to put the aircraft into a wings level pull up and climb along the current heading. However, there is no point in giving an along–track warning if this would cause the pilot to put the aircraft wings–level and fly into a cliff face which cannot be cleared at the current heading. Therefore GOCAT checks the region between the along–track flight path and the wings level flight path. The initial warning in this region tells the pilot that if a wings level pull up is to be accomplished it must be done now or any future along–track warnings will require the aircraft to climb in turning flight. This feature is particularly useful when flying along valleys. GOCAT will warn the pilot of the dangers of the side of the valley, whilst allowing him to follow the twists and turns of the valley, knowing that warnings will be generated about any terrain or obstacles along the valley floor in sufficient time to climb over them, whilst maintaining the current flight path.

The final category of warning is a no–turn warning. These indicate to the pilot whether or not there is high terrain and/or obstacles to either side of the aircraft.

3.4 Precision Navigation

The navigation requirements are met by integrating an Inertial Navigation System (INS) with Global Positioning System (GPS), Map Referenced Navigation (MRN) and Edge Detection Navigation (EDN) in a federated Kalman filter architecture.

The principles of INS and GPS are well documented elsewhere and are not discussed further here.

Map Referenced Navigation (MRN) uses data from existing aircraft sensors to construct a profile of the terrain overflown:

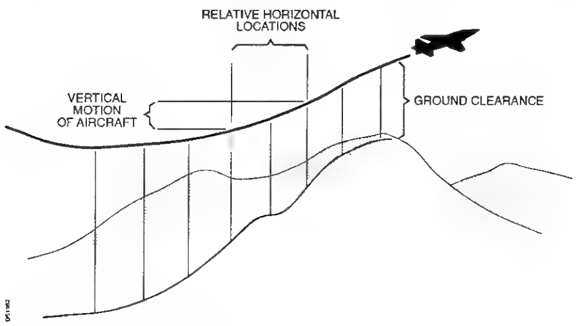

Fig. 8 MRN principles

A radar altimeter provides a sequence of ground clearance measurements, whilst barometric height or baro–inertial height is used to calculate changes in the aircraft height relative to a datum (mean sea level). These measurements, together with horizontal dead reckoning data, are used to define the measured terrain profile which is then compared with a digital terrain elevation database. The output of this comparison process is a sequence of position fixes which can be used as measurement inputs to a blending filter to correct the errors in the dead reckoning system.

The MRN navigation accuracy depends primarily on the terrain roughness and on the quality of the terrain elevation database. Extensive trials have shown that highly accurate navigation performance can be obtained from the Digital Land Mass System (DLMS) Digital Terrain Elevation Data (DTED) Level 1 database.

The vertical performance is maintained even over very smooth terrain and water.

Edge Detection Navigation (EDN) is a position–fixing technique which uses the radar reflectivity of the terrain overflown. This radar reflectivity varies according to the nature of the terrain culture and is determined by measuring the return signal strength from a specially modified radar altimeter. A low return signal strength is received from high absorption materials, such as trees and bushes, and high return signal strength from highly reflective surfaces such as water and roads. The incoming signal strength data are used to detect reflectivity changes exceeding a predetermined threshold. These 'events' mark the transition from one feature type to another.

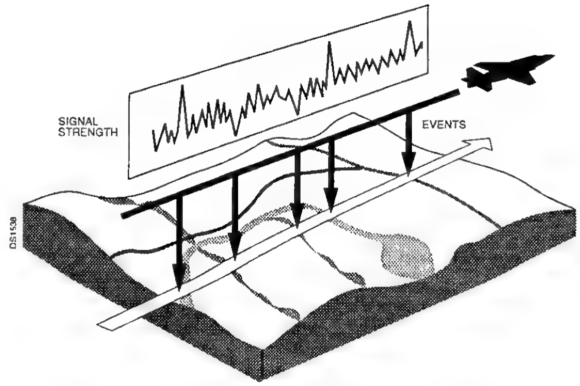

Fig. 9 EDN principles

At each event an area of digitally stored map, centred on the current best estimate of aircraft position and comprised entirely of boundary information, is sampled. The results from a sequence of events are combined, using a statistical algorithm, to produce an estimate of the true position of the aircraft. These position fixes can be integrated readily with an INS using a Kalman filter.

In addition to generating fixes, the processing within the EDN can be used to detect features and boundaries below the flight path to check that they arise when expected, based on the outputs of the other navigation systems. This technique may therefore be used to improve the integrity of the overall navigation system.

The proposed integration approach involves a federated Kalman filter architecture. A simplified block diagram is shown in Fig. 10.

The INS provides the main dead reckoning function. The outputs from the GPS, MRN and EDN functions are fed into a federated Kalman filter to provide the optimum navigation solution.

Potentially, the MRN could supply an extremely accurate height and height rate to the GPS. This information would be used by the GPS as if it were from a 'pseudo satellite' at the centre of the earth. The remaining three satellites required to form an optimum solution could be at higher elevation than would be the case for a normal 4–satellite solution. This reduces the vulnerability to terrain or culture screening and improves GPS availability. In addition, depending on the satellite geometry, the input of an accurate height can also improve the accuracy of the horizontal output.

The position and velocity corrections calculated by the fusing element are added to the raw INS outputs to yield an integrated navigation solution.

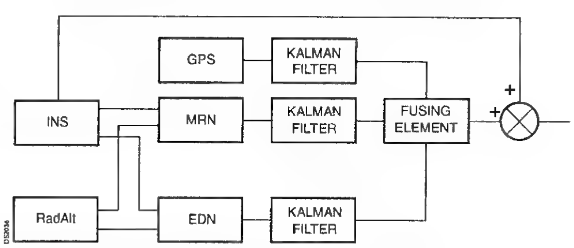

Fig. 10 Integration architecture

4. PERFORMANCE AND TESTING

The Optimum Routeing, Ground Collision Avoidance and Navigation systems have all been extensively tested using flight trials data in conjunction with ground based simulation and analysis.

In order to assess the integrated navigation system a suitable reference track is required. Such a track may be generated using photofixing, D–GPS or kinetheodolite tracking, or combinations of these. An accuracy of a few metres in the horizontal and vertical axes is required.

The MRN has been undergoing flight testing on numerous transport and combat aircraft and helicopters since the mid 1980s and reliable and consistent performance has been achieved over all terrain types. More recently EDN has been undergoing flight testing on a transport aircraft to establish the performance and to optimise the system.

The integrated navigation system was evaluated using logged aircraft sensor data as inputs to the navigation algorithms on a ground–based VAX computer. This allowed the evaluation of potential in–flight architectures and algorithms using repeatable input data. The benefits of the federated Kalman filter architecture are illustrated in Fig. 11 and 12, which show the performance of an integrated INS/GPS/MRN/EDN system using centralised and federated architectures respectively.

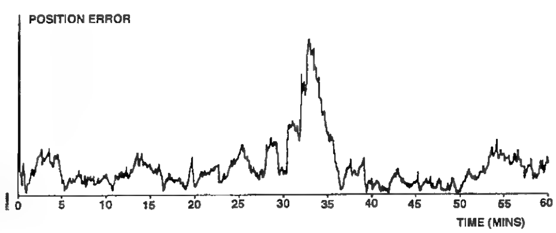

Fig. 11 Navigation performance using centralised architecture

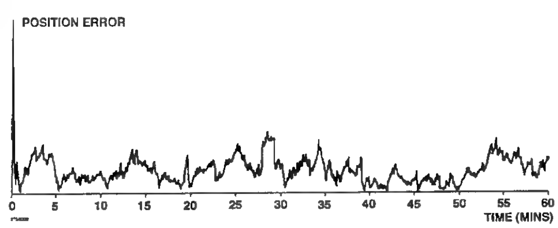

Fig. 12 Navigation performance using federated architecture

A transient error was deliberately introduced in one of the fixing systems at approximately 30 minutes into the flight. Fig. 11 shows that with the centralised architecture the transient error is undetected and, although the error is subsequently removed, its effect persists for about 5 minutes. Fig. 12 shows the same input data used in a federated architecture. It can be seen that the error is immediately detected and removed from the navigation solution.

A fully integrated system using the federated Kalman filter architecture is about to commence flight testing on a transport aircraft.

At the same time as developing a robust and accurate navigation architecture, work was being carried out on the ground proximity warning system and optimum routeing.

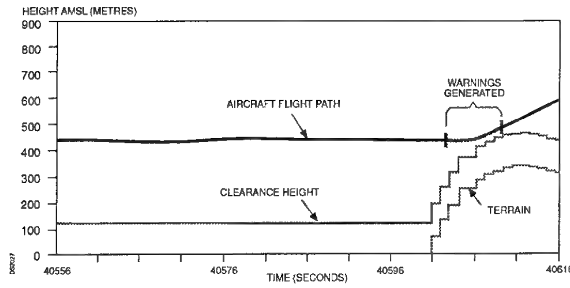

Fig. 13 GOCAT – Flight towards a cliff – warnings generated

Early work quickly demonstrated that false warnings were not generated, but that warnings were generated at the correct time if a dangerous situation was simulated by raising the specified clearance height. The next stage of development was to produce a more formal version of the code suitable for flight trials. This version of GOCAT was flown on a transport aircraft with very good results. As well as the basic pull–up warning, a number of other features were demonstrated such as no–turn warnings and warnings in turning flight for which the wings–level escape path would be potentially dangerous. Figs. 13 and 14 show two example flights over water towards a cliff. In the first the aircraft is in danger of infringing the clearance margin and a warning is generated, whereas in Fig. 14 the aircraft, although in descending flight, will still clear the cliff by the required clearance. In this case no warnings are generated.

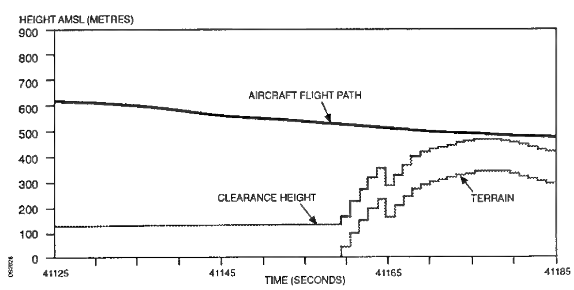

Fig. 14 GOCAT – Flight over a cliff – no warnings generated

GOCAT is also undergoing flight trials on the GEC–Marconi Avionics company aircraft. For the company aircraft the basic sensor fit was a GPS, radar altimeter and barometric height. This is representative of a number of small commuter aircraft. This system also contains a navigation element, including MRN, to monitor and optimise the GPS performance with respect to the terrain. The code for this system is written in Ada, ready for use in both a military system and, indeed, a commercial system, as the airlines are indicating that Ada is also their preferred language.

A key part of the testing has also been to demonstrate that multiple warnings are not generated due to the same terrain feature or obstacles whilst, at the same time, ensuring that a build up in the severity of the warning is generated if the pilot ignores the warning. For example, in the case shown in Fig. 7, when the forward pull–up line is breached a "terrain warning" is generated. When the second and subsequent pull–up lines are breached the severity of the warnings is systematically increased to "TERRAIN" then "pull–up" and finally "PULL UP". At the same time the logic within the system ensures that multiple "terrain" warnings for example are not generated. A further advantage of this approach is that the time between the different warning types can be set easily to a specified value giving the pilot further feed back to the current situation. The times between warnings can be easily be changed to reflect a military or commercial aircraft.

The performance of the Mission Planning System has been demonstrated on a Symbolics Workstation with a variety of scenarios. These scenarios have included a number of geographical locations and threat environments, as well as a number of air vehicle types.

An example display from a demonstration scenario set in Wales is shown in Fig. 15. This display has been designed for experimental and engineering analysis and is not necessarily representative of a cockpit display. The key elements in the display are the underlying terrain, using DTED as a source, no–go areas and threats. Threats are shown as two concentric circles, the inner being the kill region, the outer the detection area.

In Fig. 15 two routes are shown. The first route, shown as a dashed line, is the original ground plan as would be entered by the crew. It consists of straight line segments between the entered waypoints and targets. The second route, shown as a solid line, is the route produced by the Mission Planner. As can be seen in Fig. 15, the Mission Planner has taken note of the waypoints A to D entered by the crew and then produced a route up through Wales to the target (T) avoiding the no–go areas and minimising the exposure to threats.

The Mission Planner uses the terrain information to minimise the aircraft exposure to known and unknown threats throughout the mission. For known threats, the Mission Planner generates a route that maximises the terrain shielding of the aircraft from the enemy radar whenever the aircraft is forced to traverse a threat zone. For unknown threats, exposure time is kept to a minimum by keeping the aircraft as close as possible to the terrain and hidden from as many angles as possible. Because of this, the Mission Planner will tend to generate routes which will direct the aircraft along valleys and avoid flying over hill tops whenever possible.

If a new threat should appear at some time through the flight, then the Mission Planner will take account of the new threat automatically and generate a new route. This new route will be the new lowest–cost route to the target.

Fig. 16 shows a more detailed section of the route near waypoint D and the route generated by the Tactical Router. The direction of travel is up the page. The straight line is the route from the Mission Planner and the curved line the route from the Tactical Router. The short lines branching off the tactical map are examples of routes which have been rejected as unsuitable. The tactical route shown is from a number of iterations to demonstrate how it responds to a threat. For the first few iterations the tactical route is along the solid line. Later, a threat T1 is detected and the route for subsequent iterations takes account of the threat kill zone and takes the aircraft around it.

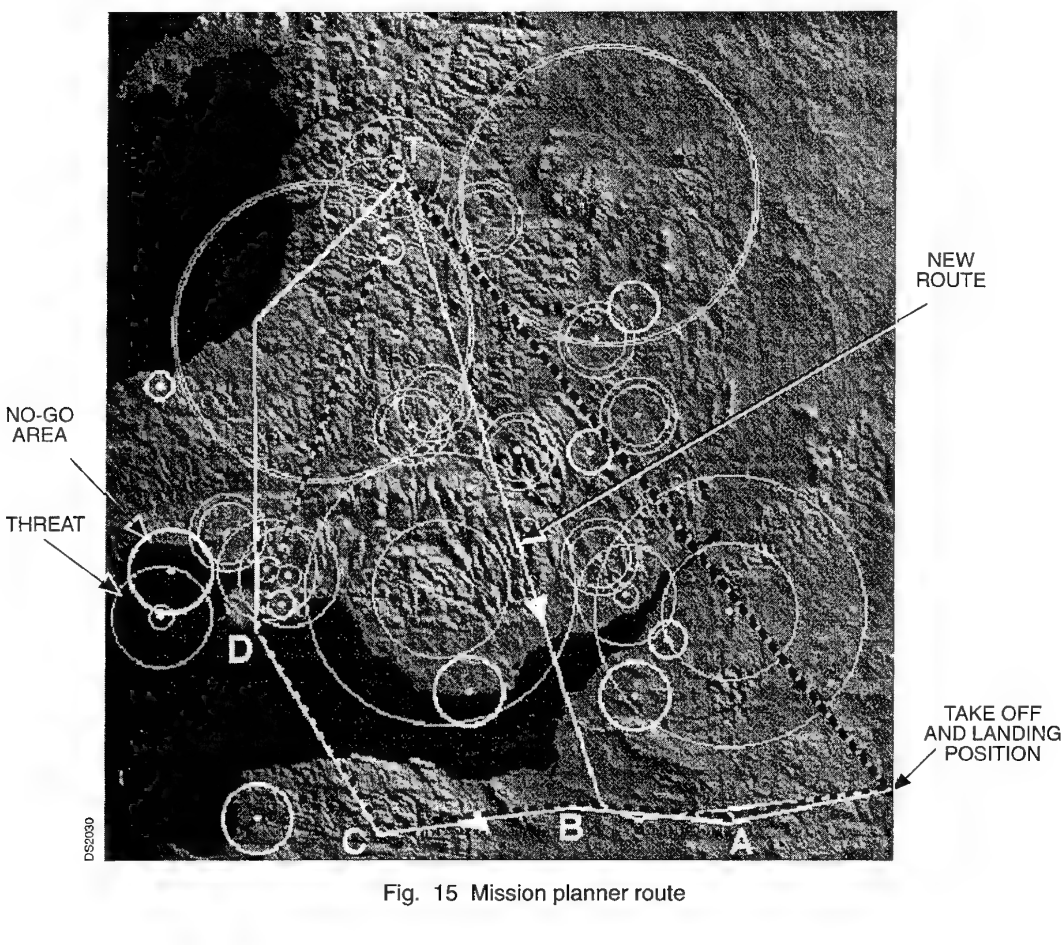

Fig. 15 Mission planner route

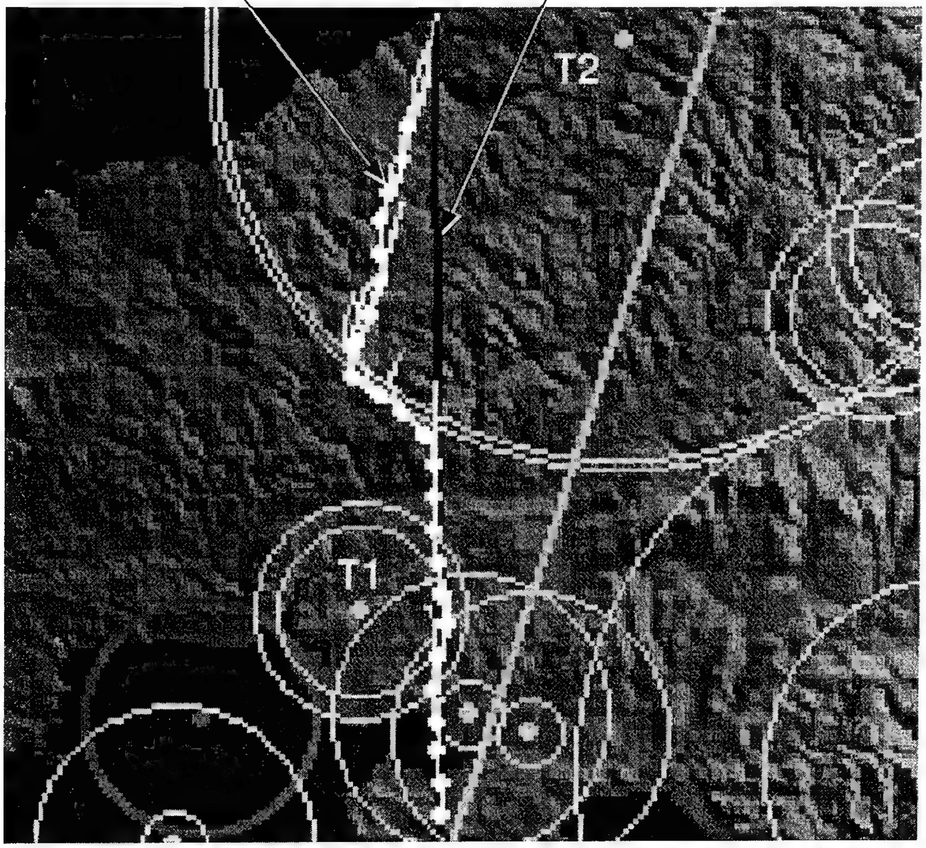

Fig. 16 Tactical route

The next threat, T2, is unavoidable and at some point the aircraft will have to fly through the threat area. However the Tactical Router reassesses the route from the Mission Planner and generates a new route which minimises the exposure time to the threat.

The tactical route is more detailed in its analysis of the current environment and hence produces a slightly different route from the Mission Planner. It also ensures that a flyable route is produced so that a curved route is flown around a waypoint rather than the straight–line sections of the mission plan.

This system is now being prepared to fly in an experimental aircraft for real time operation in the air.

5. CONCLUSIONS

The individual systems described previously all offer significant benefits to a pilot, which are further enhanced when the systems are integrated. With an integrated system the pilot workload is greatly reduced as the routine aspects of getting the aircraft to the target zone accurately and on time, have already been done. This leaves the pilot free to concentrate on the prime purpose of the Mission, to attack the target, and also to watch out for enemy forces, especially aircraft.

The combination of Mission Planning and Tactical Routeing ensures that the route taken to and from the target is the safest possible under the current threat conditions and that the aircraft reaches the target zone on time, with sufficient fuel and is approaching the target at the right heading. This route is based on a quantitative assessment of all the risk factors, rather than the pilots best guess of what to do. This is particularly relevant when something unexpected happens, such as an enemy attack causing the pilot to divert from the original flight plan. Currently, the pilot would have to take evasive action to ensure he is not shot down by the enemy fighter, whilst not flying into threat areas and avoiding the terrain. Once the pilot has done this, he must reorientate himself and work out the best way to get back to the target, avoiding any threats on the way.

All this has to be done rapidly and in a very stressful situation. With the Optimum Routeing the pilot need not worry about how to get back onto the target when he is attacked and concentrate on avoiding the enemy aircraft. He can also take advantage of GOCAT to keep the aircraft close to the ground safely if required and leave pull up manoeuvres to the last second, making it harder for the enemy aircraft to follow. Once the enemy aircraft has been dealt with the Optimum Routeing will show the pilot exactly what route to follow to reach the target, whilst maintaining the safest route to reach the target on time.

Whilst the pilot is flying the route generated by the Optimum Routeing he is relieved not only of the burden of working out the route, but also of constantly maintaining the safety of the route. The Optimum Routeing provides a four–dimensional route which takes into account the terrain and obstacles, moreover this can be fed to the flight control system so that the flight path of the aircraft is fully automatic. At the same time, GOCAT is assessing independently the flight path of the aircraft with respect to the terrain and obstacles. Therefore GOCAT provides an independent monitor to the Optimum Routeing increasing the overall integrity of the system.

For a system like GOCAT to be effective an accurate position, with respect to the terrain and obstacles is required. This is where the integration of the navigation systems has a part to play. Without accurate navigation the clearance tolerances within GOCAT would have to be enlarged to account for possible navigation errors, so that the pilot would be forced to fly higher. The accurate navigation also enables the aircraft to be flown precisely to the target, and more importantly, enables the height of the aircraft with respect to the target to be determined accurately – a key factor in weapon aiming.

A future extension to such a system would be to add a dynamic link, such as JTIDS, to allow for updates to the threat environment. The JTIDS controller would be responsible for maintaining the validity of the threat environment and integrating new threat data as it becomes known. For example, if attacking aircraft have detected new threats, this information can be fed back to the JTIDS controller whose responsibility is to collect the data from all possible sources to remove ambiguities and produce the most accurate assessment of threat position and types. This new data can be down loaded to all applicable aircraft which can take account of it with their on board Optimum Routeing systems.

6. ACKNOWLEDGEMENTS

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UNE MÉTHODE NUMÉRIQUE ORIGINALE POUR LA NAVIGATION AUTONOME

Hubert Cantalloube
Ingénieur de Recherche, Adjoint au Chef de la Division Traitement des Données
O.N.E.R.A.
BP 72, 92332 Châtillon
France

1. SOMMAIRE

Une méthode numérique originale associant les techniques classiques de filtrage, les techniques du traitement d'image et la théorie de l'évidence, est proposée pour la navigation d'engins autonomes. Les observations ambigües (confusions d'amers, fausses alarmes et non détections) sont tolérées.
L'efficacité de l'algorithme est illustrée par un exemple concret.

Mots clés :
Navigation, Recalage, Théorie de la décision, Filtrage.

2. INTRODUCTION

Cet article présente une technique de filtrage numérique pour la navigation des engins autonomes.
L'approche développée s'applique typiquement aux véhicules aériens autonomes, et permet par exemple de recaler une centrale inertielle de précision moyenne. Pour se faire, le calculateur de bord estimera la position de l'engin en temps réel à partir d'une carte numérisée du terrain (en mémoire) et des observations du paysage faites par un capteur (radar ou caméra).
Le problème principal de la navigation d'engins autonomes, réside justement dans la mise en correspondance de ces deux sources d'informations : cartographie enregistrée et observation en temps réel. On supposera qu'un prétraitement a été effectué et qu'en fait la carte mémorisée est donnée sous la forme d'une liste d'amers répertoriés par des techniques classiques d'imagerie. Ce point sera précisé dans la suite.
Les difficultés rencontrées sont inhérentes aux capteurs utilisés : par exemple, la préparation de la mission est généralement faite à partir d'une image SPOT tandis que l'image du terrain survolé au cours de la mission est obtenue par un radar SAR. Quatre types d'erreurs peuvent alors se produire : les non–détections, les fausses alarmes, les confusions et enfin les distorsions de l'image "temps réel".

2.1 Non–détections

Un amer cartographié peut être invisible à l'observation :
– soit parce qu'il n'existe plus (c'est le cas par exemple de la séparation entre deux champs qui a disparu entre le moment où la carte a été élaborée et où le véhicule effectue sa mission),
– soit parce qu'il n'a jamais existé (erreur de cartographie),
– soit parce qu'il est invisible pour le capteur embarqué alors qu'il l'était par le système utilisé lors de la préparation de la carte, (c'est le cas notamment pour les cartographies établies à partir d'images satellite en lumière visible et infrarouge, utilisées pour préparer les missions d'un engin équipé d'un radar),
– soit enfin par le fait du hasard et des algorithmes de traitement d'image (par exemple pour les images radar, les statistiques des intensités mesurées sont souvent approximées en xe^{-x^2} ce qui peut faire passer un point ou un contour en dessous du seuil de détection).
Le taux de non détection τ_{ND} ou la probabilité de non détection P_{ND} dépendent essentiellement de la nature de l'amer et des conditions d'observation (distance, incidence, cap de l'engin, mais aussi conditions atmosphériques etc...).

2.2 Fausses alarmes

Un amer non cartographié peut avoir été détecté :
– si l'existence de l'amer est réelle, il se peut qu'il n'ait pas été "vu" par le système utilisé pour établir la cartographie ou bien qu'il ait été jugé non significatif.
– une fausse détection peut avoir eu lieu (amer inexistent) à cause du speckle (effet de scintillement des images obtenues par un radar sur un terrain rugueux) et du traitement d'image employé.
Le taux de fausse alarme τ_{FA} dépend du type d'amer et de la position observée dans l'image.

2.3 Confusions possibles

Un amer observé peut être confondu avec plusieurs amers cartographiés ressemblant ou identiques (pylônes haute tension par exemple). Cette ambiguïté est pratiquement de règle et interdit donc l'utilisation directe d'un filtre de Kalman pour le recalage de navigation (A l'exception cependant des systèmes de recalage par radio–phares comme celui utilisé à bord de l'Airbus A320 puisque chaque radio–phare émet un signal d'identification qui lui est propre).

2.4 Distorsions de l'image

Elles apparaissent souvent suite à une erreur dans la

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connaissance de la trajectographie exacte du véhicule pendant l'acquisition. Elles entrainent nécessairement des erreurs dans le positionnement de l'amer.

Pour rester performant, un filtre de recalage doit être extrêmement "tolérant" vis à vis des informations erronées et doit pouvoir extraire de toutes les observations contradictoires qu'il reçoit, un sous-ensemble maximal cohérent (correspondant aux vraies détections de vrais amers et aux fausses alarmes en coincidence fortuite avec les amers faussement cartographiés).
D'autre part, le résultat du filtrage ne doit pas dépendre de manière trop sensible de paramètres difficiles à évaluer tels τ_{ND} et τ_{FA} qui devraient alors être déterminés pour tous les amers cartographiés et toutes les positions possibles !

La technique de filtrage D^2P (Diffusion des Densités de Présence) qui va être décrite dans le paragraphe 3, est inspirée des techniques bayésiennes classiques. Pour le problème qui nous concerne, l'état du filtre à l'instant t est par définition la densité de probabilité de présence du véhicule $p(X_t)$. En toute rigueur, X_t devrait être un point de l'espace 3D mais nous supposerons pour des raisons technologiques que l'altitude z de l'engin est déterminée par ailleurs (radio-sonde, utilisation du premier écho SAR ou barymétrie). De ce fait p sera assimilée à une densité de la position $X_t=(x_t,y_t)$. Généralement, cette densité $p(X_t)$ est modélisée par une gaussienne et est donc déterminée de manière univoque par cinq paramètres (deux moyennes et trois valeurs pour la matrice de covariance 2x2). Pour le filtre D^2P la densité ne sera pas forcément gaussienne.

Les filtres classiques procèdent en deux étapes dites de prédiction et de correction. Pour cela, on modélise l'évolution de l'état en fonction du temps par une équation généralement linéaire (équation d'état) de la forme :

$$X_{t+1} = FX_t + \Gamma v_t \qquad (1)$$

où v_t est un bruit supposé gaussien.
Par conséquent, connaissant la densité $p(X_t)$ il est possible de prédire la densité de probabilité de présence de X_{t+1} puisque :

$$p(X_{t+1} | X_t) = p(FX_t) * p(\Gamma v_t) \qquad (2)$$

L'opération de convolution conserve le caractère gaussien des densités et donc $p(X_{t+1} | X_t)$ est une densité gaussienne de moyenne $\bar{X}_{t+1}$ et de covariance P_{t+1} données en fonction de $\bar{X}_t$ et P_t par :

$$\begin{cases} \bar{X}_{t+1} = F\bar{X}_t \\ P_{t+1} = FP_tF^T + \Gamma\Gamma^T \end{cases} \qquad (3)$$

Pour la partie correction de l'état, le filtrage de Kalman suppose qu'une seule mesure Z_{t+1} (qui peut bien sûr être vectorielle) a été effectuée au temps t+1, et que cette mesure peut être reliée à l'état par une équation d'observation linéaire, de la forme :

$$Z_{t+1} = HX_{t+1} + w_{t+1} \qquad (4)$$

L'état est mis à jour simplement

$$p(X_{t+1} | Z_{t+1}, Z_t, \ldots, Z_0) = p(X_{t+1} | Z_{t+1}) \cdot p(X_{t+1} | Z_t, \ldots Z_0) \qquad (5)$$

Cette relation est établie par la formule de Bayes classique,

$$p(A,B) = p(A|B)p(B) \qquad (6)$$

pour deux évènements A, B non nécessairement indépendants.
Le produit de deux densités gaussiennes est une densité gaussienne dont on peut formuler la moyenne et la variance. On établit ainsi l'évolution des cinq paramètres qui caractérisent la densité $p(X_t)$.

Le Filtre à Association Probabiliste de Données, PDAF (Probabilistic Data Association Filter) développé par Bar Shalom [1] est une version améliorée du filtre de Kalman qui prend en compte l'existence de plusieurs mesures ou observations au temps t+1. Le calcul de l'innovation classique est remplacé par une combinaison linéaire des innovations élémentaires correspondant à chacune des observations. Les coefficients de la combinaison linéaire dépendent d'une part de la distance entre l'observation et la prévision (typiquement par la valeur d'une densité gaussienne de covariance triple de celle de l'état propagé au temps t) et d'autre part de la qualité de l'association objet/observation au travers d'une matrice de confusion et d'une identification incertaine (voir [2]).
La densité ainsi obtenue est approximée par la gaussienne de même moyenne et même covariance, et est utilisée comme observation par un filtre de Kalman. A ce procédé est ajouté une étape de "fenêtrage statistique" qui élimine les amers "statistiquement improbables" ou les mesures aberrantes.

L'algorithme de filtrage D^2P explicité sur la **Figure 1** s'appuie sur une modélisation discrète markovienne du processus stochastique qu'est la position $X_t=(x_t,y_t)$ du véhicule au cours du temps. L'état du filtre, est une densité de probabilité de présence discrète définie aux noeuds d'un maillage rectangulaire d'une région rectangulaire de l'espace. Si l'état est bien "concentré" au voisinage d'un seul noeud du maillage, on pourra assimiler les positions successives du pic de densité de probabilité à la trajectoire estimée de l'engin. Si par contre l'état est une densité multimodale, il y a ambiguïté sur la position.
Néanmoins, à la différence du filtre de Kalman, l'hypothèse que le processus est markovien n'est qu'une approximation. En effet, l'erreur de position (deux degrés de liberté) dépend en fait de trois variables aléatoires : intégrales doubles des erreurs accélérométriques et erreur en cap. La densité de probabilité de présence, ne décrit plus alors rigoureusement l'état du système. Il faudrait

pour cela intégrer le cap à l'état du système (ou l'erreur angulaire de la centrale inertielle) ou encore considérer un maillage tri-dimensionnel de l'espace. Ceci semble peu compatible avec les technologies d'aujourd'hui avec les performances et le coût attendus pour un système destiné à économiser sur la centrale inertielle !

La prédiction de l'état qui donne donc $p(X_{t+1}|X_t)$, se fait par produit de convolution comme pour les filtres classiques, grâce à l'équation du mouvement de l'engin. Cependant comme la densité de probabilité de présence $p(X_t)$ n'est pas nécessairement gaussienne, la convolution est menée numériquement sur toute la région d'intérêt. L'équation de correction est établie par une formule de style "Bayes" mais elle tient compte des ambiguïtés évoquées plus haut : fausses alarmes, non détections et confusions d'amers.

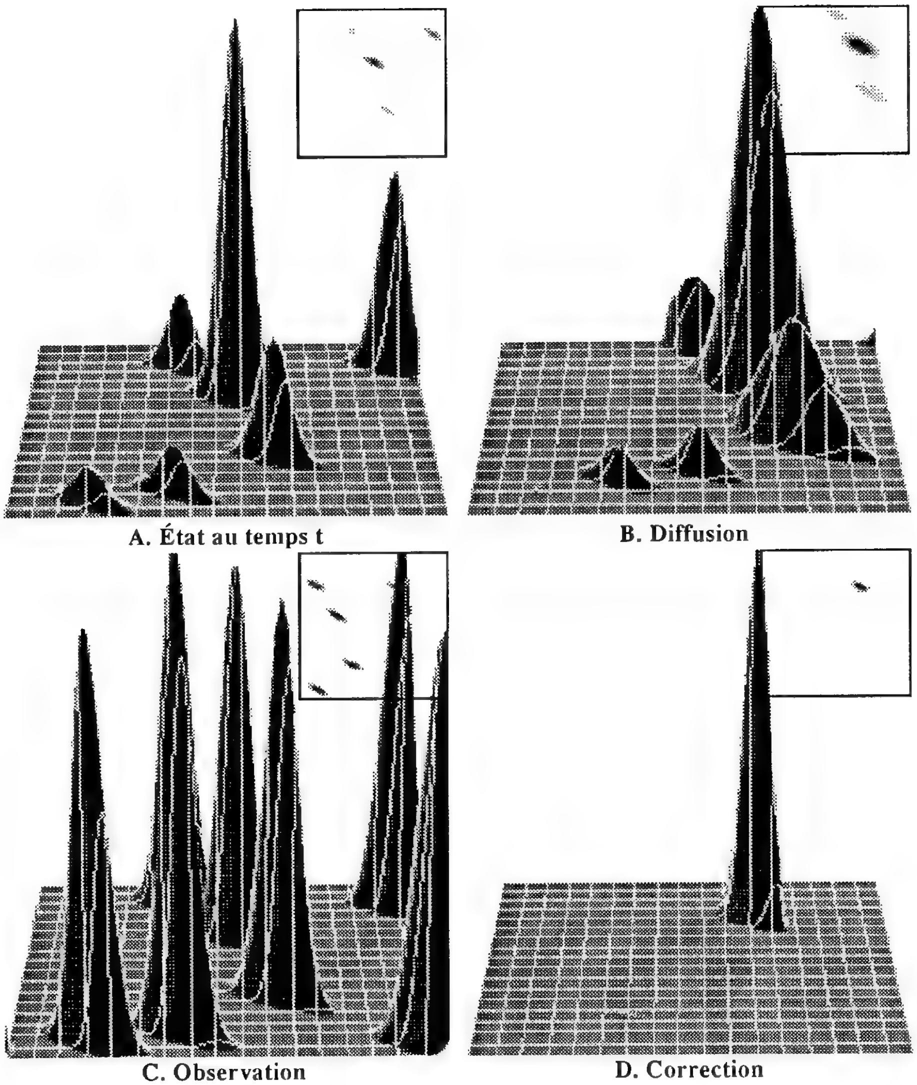


Figure 1 : Principe du filtrage D^2P

Le filtre de Kalman suppose l'innovation gaussienne c'est–à–dire que l'observation d'un amer (nécessairement unique) donne la position relative de l'amer avec une erreur de densité gaussienne. Une telle approche exclut toute ambiguïté dans la reconnaissance de l'amer. Le filtre PDAF tolère l'ambiguïté en intégrant l'état propagé au temps t et des indices de qualité (confusion entre types) aux observations, pour pondérer les alternatives dans le cas d'une observation multiple.

L'innovation reste toutefois gaussienne, c'est–à–dire que les ambiguïtés sont traitées à chaque temps t. Par exemple, si l'engin traverse une ligne haute tension –dont les pylônes sont distants de 500m– au niveau d'un pylône (position relative à σ=5m), et que la position estimée *a priori* se trouve juste entre deux pylônes avec une incertitude de 500m, l'innovation sera gaussienne centrée entre les deux pylônes avec une variance σ de 5m dans la direction perpendiculaire à la ligne haute tension et un σ de 500m dans la direction parrallèle. On remarquera que la densité correspondante est centrée sur un point (juste entre les deux pylônes) où l'on sait justement que le véhicule ne se trouve pas ! Pourtant, le filtrage PDAF fonctionne bien dans ce cas car l'état n'est "reserré" que dans la direction orthogonale à la ligne traversée. Le PDAF réagit en fait comme un filtre de Kalman quand il n'y a pas d'ambiguïté, comme un filtre de navigation par franchissement quand les positions candidates sont alignées et évite de mettre à jour l'état dans les autres cas.

L'originalité du filtre D^2P réside dans la fusion des observations contradictoires ou ambigües au niveau de l'équation de Bayes (avec normalisation pour obtenir une probabilité puisque les contradictions font que la somme des densités est inférieure à un) de mise à jour et non plus au niveau de l'élaboration de l'innovation.

On ajoute à cet algorithme une dernière étape qui n'a pas d'équivalent dans le filtre de Kalman, qui consiste à décider de la position du véhicule en fonction de l'état. Dans le cas des filtres de Kalman et PDAF, la position la plus probable est la moyenne de l'état, la covariance donnant une estimation de la précision. Dans une modélisation numérique du processus de présence, la position la plus probable peut ne pas correspondre à un noeud du maillage de l'espace. Mais la difficulté majeure est que cette position, la plus probable, dépend des performances attendues. Celles–ci sont par exemple définies en termes de probabilité de destruction de cibles désignées si le véhicule est un drône, en fonction de la distance d'impact.

Supposons pour illustrer ce phénomène que la probabilité de présence ait la structure (d'école) définie par : un pic très étroit contenant 20% de la probabilité de présence et à 200m de là, une répartition uniforme sur un cercle de 100m de rayon contenant 80% de la probabilité de présence. Suivant le type d'armement dont on dispose, la décision sera différente.

En effet, si l'on utilise une charge qui détruit avec une probabilité de 80% sur une distance inférieure à 100m et 5% entre 100 et 200m, il vaut mieux centrer le tir sur le centre du cercle. Si par contre la destruction n'est assurée que sur une distance inférieure à 50m il vaudra mieux tirer sur le pic de densité.

Le paragraphe 3 détaille les étapes du filtre de navigation : calcul de l'innovation, mise à jour, diffusion (l'étape de décision dépend de l'application). Le paragraphe 4 est consacré à un exemple concret qui illustre les performances et les originalités de la méthode implémentée.

3. ÉTAPES DU FILTRAGE D^2P

Le capteur utilisé pour la navigation fournit une image incomplète du terrain survolé. En effet, les objets détectés ne peuvent pas d'emblée être positionnés par rapport à l'engin (il manque pour retrouver les coordonnées relatives la connaissance de la distance si une caméra est employée et celle du gisement dans le cas d'un radar). En théorie, si la trajectoire du porteur était parfaitement connue au cours de l'acquisition, l'image pourrait être rétroprojetée sur la surface du terrain. On obtiendrait ainsi une carte de la réflectivité radar ou de la luminosité dans le cas d'une caméra, en fonction des coordonnées géographiques incluant l'altitude. Une telle reconstruction 3D suppose que le problème de navigation a été déjà complètement résolu.

Pour l'opération de recalage, on considèrera deux catégories d'amers :

– Les amers ponctuels dont le type est déterminé par des techniques d'imagerie et appartient à un ensemble discret fini A_p

$$A_p = \{ \, type_1 \, , \, type_2 , ... type_p \, \}$$

Ce sont par exemple des bâtiments isolés, des pylônes haute tension, des châteaux d'eau, des clochers etc...

– Les amers linéaires dont le type est cette fois défini par une variable discrète appartenant à un ensemble fini A_l, et une variable continue ω de $[0,\pi[$ si l'orientation est indifférente (route ou séparation entre champs) ou de $[0,2\pi[$ s'il y a lieu de faire une distinction entre droite et gauche de la ligne (lisière de forêt).

On supposera que la carte mémorisée est donnée sous la forme d'une liste de points et de vecteurs :

$$\left\{ \text{position(s) } x, y \,\&\, z, \text{ erreur(s) } \delta x, \delta y \,\&\, \delta z, \text{ type, taux de fausse alarme } \tau_{FA} \right\}$$

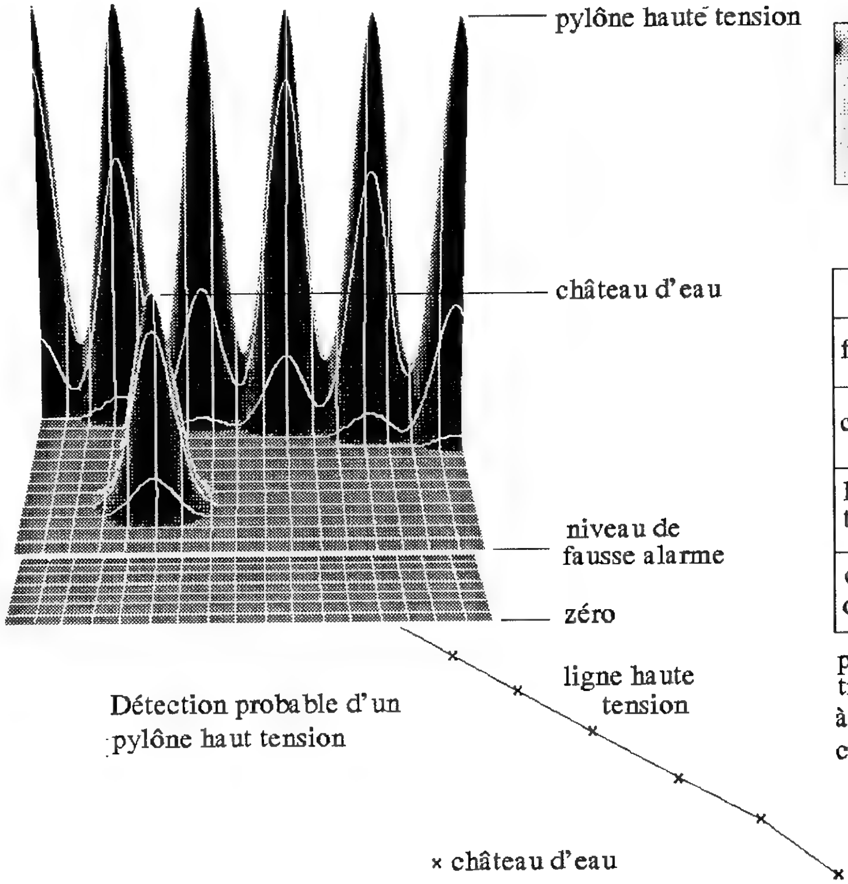
En toute rigueur, le taux de fausse alarme dépend de l'amer et il faudrait considérer un vecteur de taux. Pour les amers linéaires, on donne une liste de vecteurs spécifiés par les positions et les erreurs des deux extrémités.

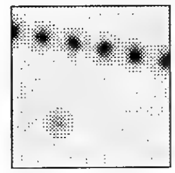
Au cours de la mission, un amer de type i peut être confondu avec un amer de type j. Si $\tau_{i,j}$ désigne la probabilité de confusion, on a :

$$\sum_{j=1}^{p} \tau_{i,j} = 1 \qquad (7)$$

avec $\tau_{i,0}$ probabilité de non–détection d'un amer de type i.

Remarquons que l'on peut aussi, selon la théorie de l'évidence [3] et comme décrit sur la Figure 2, considérer un jeu de masse $m_{i,j}$. Il y a alors 2^p-1 termes dans la somme.





amer	poids
fausse alarme	0,1
château d'eau	0,2
pylône haute tension	0,5
château d'eau ou pylône	0,2

poids attribués par le traitement d'image à à partir des données capteur

Figure 2 : Décision incertaine

3.1 Préliminaire

Avant de formuler l'équation de mise à jour de l'état, il est nécessaire de calculer $p(O_i|X)$, la densité de probabilité d'observation d'un amer de type i connaissant la position X=(x,y) de l'engin. On supposera ici les observations indépendantes.

L'observation peut être une détection si l'amer est effectivement signalé sur la carte en mémoire, une fausse alarme, si l'amer n'est pas mentionné sur la carte en mémoire. Mais il se peut qu'il y ait une non–détection, pour les amers listés en mémoire qui auraient dû être observés de la position X.

Le cas de la détection est en fait plus complexe qu'il n'y paraît car l'amer observé peut être associé à un amer listé en mémoire, de type distinct à cause des aléas du traitement d'image. Pour les amers linéaires, la difficulté est accrue car la vectorisation d'une ligne en segments de droite peut être faite différemment entre l'image observée et le modèle cartographique en mémoire.

Soit $O_i=(O_{i,x},O_{i,y})$ un amer observé (associé à un amer répertorié de type i), $A=(A_x,A_y)$ la position cartographiée et X=(x,y) la position réelle du véhicule. On désigne par Π_X^{-1} la rétroprojection de l'image sur le terrain, au point X. En toute rigueur, Π_X^{-1} peut dépendre du point A si l'altitude à la verticale du véhicule est supposée connue, alors la distance verticale sera égale à :

altitude mesurée + altitude du sol au point x – altitude de l'amer

Pour les amers ponctuels, on démontre que

$$P(O_i|X) = \left(\sum_{j=1}^{type_p} w_j \tau_{i,j}\right) g\left(\Pi_X^{-1}(O_i) - A\right) + \tau_{FA,i}\left(1 - g\left(\Pi_X^{-1}(O_i) - A\right)\right) \qquad (8)$$

La fonction g est une fonction caractérisant l'erreur et donc typiquement une densité de probabilité gaussienne centrée. Dans la pratique, on prendra une approximation quadratique d'une gaussienne d'écart type fixé (obtenue simplement par une convolution triple d'une fonction carrée). Mais ce choix n'est pas critique, la fonction g doit quantifier de manière approximative les erreurs probables de détermination de la position des amers ponctuels (dues au capteur, à la cartographie ou au traitement d'image). On pourrait même utiliser une fonction g_i qui dépend du type de l'amer mais ceci augmenterait le coût de calcul et n'est pas justifié ici.

Pour les amers linéaires la formule se complique mais est du même style.
La formule donnant $P(O_i|X)$ est en fait inexacte pour l'altitude puisque la valeur qui va être utilisée pour la rétroprojection Π_X^{-1} est l'altitude *moyenne* du segment. Dans le cas de segments horizontaux (bâtiments, voies ferrées, cours d'eau etc...) cette simplification ne présente aucun problème. Par contre dans le cas de lignes de pente forte, cela introduit une erreur. Mais au prix d'un découpage du segment en sous–segments et donc d'une augmentation du coût de calcul, cette erreur peut être diminuée. Une autre solution serait d'augmenter l'écart type de la fonction g pour ce type d'amers ce qui aurait pour conséquence immédiate de réduire l'efficacité du recalage sur ces amers.

Le traitement des non–détections sera encore moins précis si l'on veut garder un coût de calcul raisonnable. (En fait l'implémentation du filtre $\mathbf{D^2P}$ a montré qu'il n'était pas crucial de traiter les non–détections.) La non–détection d'un amer bien visible sur la cartographie, peut toutefois lever certains cas d'ambiguïté. Supposons que sur l'exemple de la **Figure 2**, cité en introduction, une autoroute passe à côté de l'un des pylônes. Si τ_{ND} vaut 5%, ne pas détecter l'autoroute ramène à 95% la densité de présence sur les autres pylônes. La densité de présence vaudra donc 95% avec σ=5m sur un autre pylône et 5% avec le même σ sur le pylône survolé. Ce résutat doit être comparé avec ce que donnerait le **PDAF** dans cette situation : position entre les deux pylônes avec un écart–type de 5m dans la direction parallèle et de 500m dans la direction orthogonale. Le filtre de Kalman quant à lui ne recalerait pas l'engin à cause de l'ambiguïté.

Pour le seul traitement des non–détections, le sol va être supposé plan dans la région survolée, ce qui impose de prendre une fonction d'erreur g d'autant plus large (écart–type grand) que la région a un relief prononcé. Ceci n'est pas gênant en pratique car les non–détections servent plus à lever des ambiguïtés qu'à affiner la position. On le voit clairement sur la répartition de la densité correspondant à la non–détection d'amers (ce qui se produit quand rien n'est visible par un radar par exemple). Elle vaut presque partout 1 et se rapproche de τ_{ND} à proximité immédiate des amers. Comme les amers ne recouvrent qu'une petite partie du terrain (le temps de calcul et les ambiguïtés deviennent importants sinon), les maxima de la densité sont l'ensemble des points à 1 et sont donc éloignés de plus de 3 écart–type des amers. La précision de la localisation du maximum est dans ce cas une notion vide de sens.
Notons qu'il est possible de travailler avec une carte très riche (par exemple une carte des parcelles agricoles) mais dans ce cas, il ne faut pas implémenter l'algorithme de traitement des détections et fausses alarmes par comparaison des amers observés et modélisés par paires, mais procéder de la même façon qu'ici pour les non–détections.

L'altitude moyenne du terrain peut être définie de trois façons :
– Au départ par moyenne sur toute la région survolée
– Par intégration de l'altitude par rapport à la densité de présence *a priori* décalée de l'écart δ entre la position du véhicule et le centre de l'image

$$z_{moy} = \int z(X+\delta)p(X)dX \tag{9}$$

– Par calcul de l'altitude moyenne du sol et de sa dispersion, au voisinage de la position courante du véhicule.

$$z_{moy}(\delta) = \int z(X+\delta)p(X)dX \tag{10}$$

L'écart–type correspondant vaut,

$$\sigma_z(\delta) = \int (z(X+\delta)-z_{moy}(\delta))^{2p}p(X)dX \tag{11}$$

L'avantage du troisième calcul (même si la complexité est accrue) réside dans le fait qu'il fournit une bonne indication de la précision de la rétroprojection. D'autre part, si la position est relativement bien connue, la rétroprojection obtenue est optimale.

3.2 Équation de mise à jour "Bayes"

L'équation de mise à jour du filtre n'est pas exactement celle de la théorie bayésienne puisque la densité $p(X|O_i)$ n'a pas une intégrale de 1 (à cause des confusions, faux échos et non–détections).
Posons :

$$E = 1 - \int_{espace} p(O_i|\,X)dX \tag{12}$$

E représente une mesure de l'incohérence des observations. Cette incohérence peut être non nulle en cas de fausses alarmes ou d'erreur de positionnement des amers mesurés.
Tenant compte de cette remarque, l'équation de mise à jour s'écrit :

$$p(X|O_i) = \frac{p(O_i|X)p(X)}{(1-E)p(O_i)} \tag{13}$$

Le facteur $p(O_i)$ est aussi un facteur de normalisation (probabilité d'observation *a priori*) défini par :

$$p(O_i) = \frac{1}{1-E}\int_{espace} p(O_i|X)p(X)dX \qquad (14)$$

De ce fait l'équation de mise à jour se simplifie en :

$$p(X|O_i) = \frac{p(O_i|X)p(X)}{\int_{espace} p(O_i|X)p(X)dX} \qquad (15)$$

3.3 Équation de prédiction

L'équation de prédiction fournit la probabilité pour que l'engin se trouve en position X au temps t+1, à partir de $p(X|O_i)$.
Elle consiste en fait à convoluer $p(X|O_i)$ par une gaussienne (en pratique ce sera un masque 3x3 de même covariance). Soient V la vitesse aérodynamique du véhicule et ψ son cap inertiel (au temps t) supposés gaussiens de covariance respectives P_V et σ_ψ. Alors la densité gaussienne 2D traduisant le mouvement de l'engin est centrée en :

$$M = \begin{bmatrix} V\cos(\psi) \\ -V\sin(\psi) \end{bmatrix} \qquad (16)$$

et sa matrice de covariance vaut,

$$\Sigma = P_V + V\sigma_\psi \begin{bmatrix} \cos(\psi)^2 & -\sin(\psi)\cos(\psi) \\ -\sin(\psi)\cos(\psi) & \sin((\psi)^2 \end{bmatrix} \qquad (17)$$

En pratique, la translation du vecteur $\begin{bmatrix} V\cos(\psi) & -V\sin(\psi) \end{bmatrix}^T$ est fictive, puisqu'on décale l'origine de l'image de densité. Ceci présente le double avantage de ne pas propager les erreurs d'arrondi et de ne pas demander de temps calcul !

3.4 Décision

Si la densité de probabilité de présence $p(X_{t+1})$ prédite est monomodale et en "forme de cloche", alors le vecteur position est donnée sous la forme d'une gaussienne qu'on utilise par exemple pour recaler la centrale en vitesse et en cap (hybridation).

Si par contre la position est ambigüe c'est-à-dire que la densité est multimodale, on ne peut pas hybrider la centrale (sauf en utilisant le même type de filtre dans la centrale mais comme il y a trois erreurs, deux accélérométriques et une gyroscopique, l'état serait une densité 3D ce qui n'est pas encore envisageable d'un point de vue puissance de calcul et taille mémoire nécessaire. La position doit être décidée mais paradoxalement, cette décision va dépendre de l'usage que l'on va en faire.

Le cas le plus fréquent est l'utilisation de l'engin pour la destruction d'une cible donnée à l'aide d'une charge explosive embarqué à bord. La décision dépend de l'efficacité de la charge. Soit $D(\varepsilon)$ la probabilité de destruction de la cible en fonction de la distance ε entre la position de la cible et celle de l'impact. L'allure de la fonction D est très variable selon la cible et la munition. Par exemple, pour une munition anti-blindés à capacité de guidage terminal, D est approximativement constante tant que la cible est dans le champ de l'auto-directeur en fin de vol. Dès que l'écart ε sort de cette région, D est pratiquement nulle.
Par contre, pour une munition à effet de souffle utilisée contre un bâtiment non fortifié, D ressemble à une courbe en cloche.

La probabilité de destruction correspondant à une décision X_0 que nous noterons $P_D(X_0)$ est la convolution des densités de probabilités de présence et de destruction donc

$$P_D(X_0) = \int_{espace} D(X-X_0)p(X)dX \qquad (18)$$

La décision consiste à choisir (parmi les candidats) la position X_0 qui maximise cette probabilité.
Comme la densité de probabilité p(X) est définie aux noeuds d'un maillage rectangulaire, il faut discrétiser la fonction D. La convolution sera alors remplacée par une somme discrète. Nous ne détaillerons pas ce point.

4. ILLUSTRATION

Pour les simulations, la carte de référence est obtenue à partir d'une image SPOT panchromatique et d'un modèle numérique du terrain sur lesquels un algorithme classique de détection des contours a été appliqué (Figure 3.A). Le véhicule est équipé d'un radar à synthèse d'ouverture (SAR) qui fournit une image en temps réel du terrain (Figure 3.B).

Figure 3.A : Carte de référence

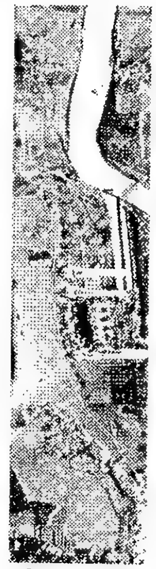
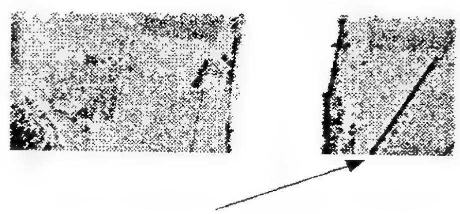


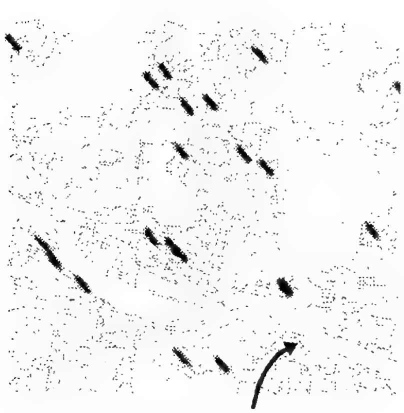
Figure 3.B : Image SAR

Le filtre D^2P a été initialisé avec une densité de probabilité de présence uniforme sur un carré de 9Km de côté. La **Figure 4** montre l'état du filtre après détection du 13ème amer (une ligne de séparation entre de champs visible avec un radar basse incidence).

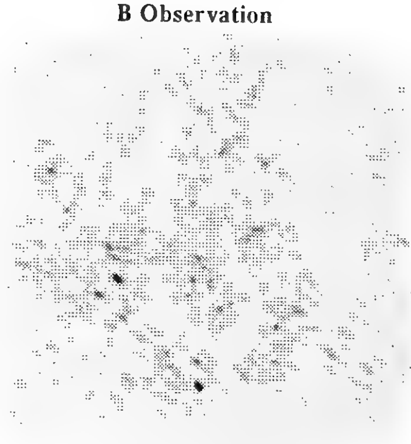
A État au temps t



B Observation



C Innovation



D Diffusion

Figure 4 : Illustration du processus de filtrage

La Figure 4.A montre l'état du filtre avant la 13ème observation. Elle correspond à la Figure 1.A. La Figure 4.B montre la 13ème observation ainsi que l'image radar disponible à ce moment. La Figure 4.C représente la carte de l'innovation p(O|X). L'amer observé n'était pas indiqué sur la carte de référence (car trop étroit pour être vu de l'espace). Enfin la Figure 4.D montre l'état du filtre après diffusion et correction. Comparé à la Figure 4.A (avant observation) il y a un accroissement des maxima locaux dû au fait que l'amer observé n'est pas sur la référence. L'algorithme converge néanmoins et la Figure 5 montre la trajectoire de l'engin et la correspondance entre carte de référence et image SAR. Les cercles indiquent la variance sur l'erreur de position.

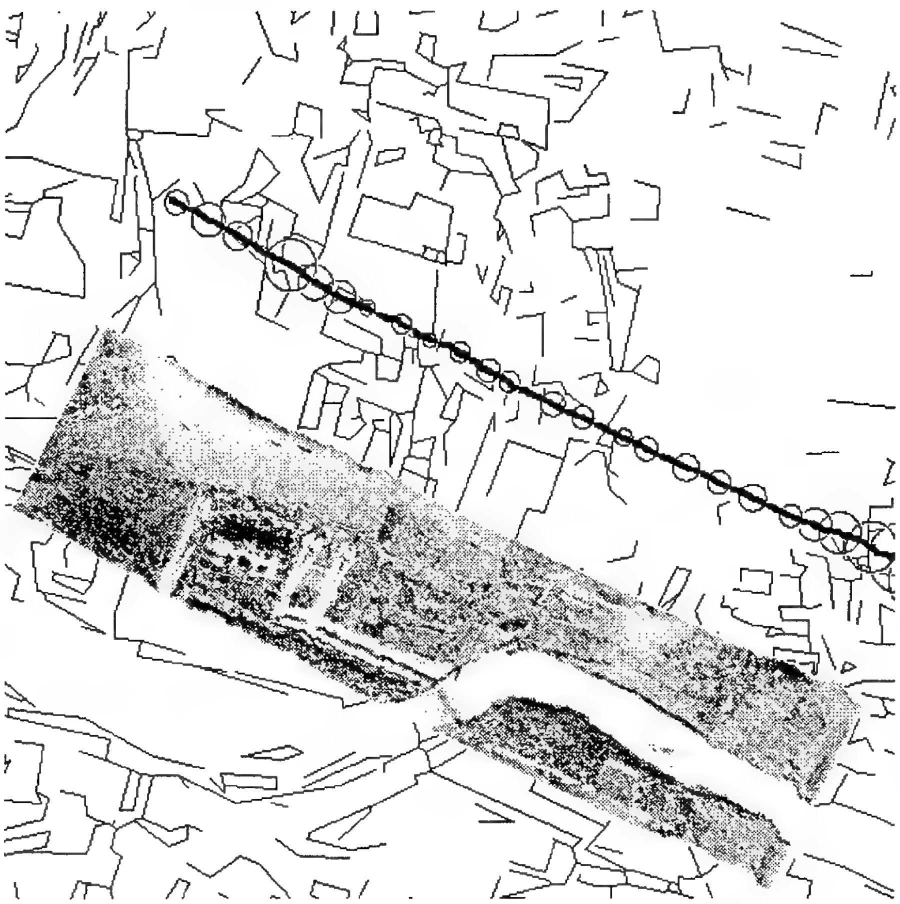


Figure 5 : Trajectoire de l'engin

5. CONCLUSION

Le fitre numérique à Diffusion des Densité de Probabilité D^2P proposé dans cet article présente deux avantages majeurs comparé aux filtres bayésiens classiques (Kalman ou PDAF) :

– Tout d'abord, à chaque itération, il traite numériquement une image de densité de probabilité et ne nécessite donc pas l'hypothèse gaussienne. Ceci permet entre autre de considérer non seulement des amers ponctuels mais aussi des amers linéaires.

– En second lieu, les observations ambigües telles les fausses alarmes, les non détections ou les confusions d'amers, sont tolérées. Ceci facilite la préparation de la mission.

Un exemple concret a montré l'efficacité de la technique pour la navigation d'engins autonomes.

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THE APPLICATION OF HELICOPTER MISSION SIMULATION TO NAP-OF-THE-EARTH OPERATIONS

P. R. Birkett
D.W.Roden
Defence Research Agency
Farnborough, Hants, GU14 6TD, UK.

1. SUMMARY

This paper describes some of the system trade-offs and integration issues associated with the next generation of battlefield helicopters operating in the nap-of-the-earth environment. The interactions between weapons, sensors, aircrew and the platform itself are discussed and their influence on the effectiveness of the helicopter as a total system is considered. Finally, an approach to the study of helicopter system integration is presented. The "multiple-man-in-the-loop" mission simulator, HOVERS, is described and its application to a typical trade-off issue discussed.

2. INTRODUCTION

In recent years, world-wide political changes combined with advances in technology have contributed to the rapid development of the role of the military helicopter. In the future, it is likely that rotary-wing aircraft will be increasingly deployed not only in high intensity conflict, but also in low intensity operations such as those associated with UN peace keeping and peace making. Furthermore, as illustrated by the Gulf conflict, the capability to operate effectively in poor weather and throughout the 24 hour battlefield day is likely to be a decisive factor in future conflicts.

The growing complexity and associated cost of modern aircraft systems places an increasing emphasis on survivability and operational effectiveness in all types of operation. In order to fulfil its potential within the battlefield context, the fighting helicopter must operate nap-of-the-earth (NOE), minimising its exposure to threats, and be able to exploit its inherent high mobility and firepower. In such scenarios, the capability of the helicopter to fulfil its roles effectively is critically dependent on the integrated operation of the sensors, mission systems, weapons, platform and aircrew. Thus it is important to consider the operational impact of the <u>total helicopter system</u> and to establish an understanding of how the various sub-systems contribute to the effectiveness of the aircraft as an integrated weapon system.

In this paper, the trade-offs concerned with the principal components of the fighting helicopter are discussed. The use of "man-in-the-loop" mission simulation to address these issues is presented, together with appropriate examples. The DRA Farnborough mission simulator, HOVERS, which has been developed specifically for study of system trade-offs in low-level helicopter operations, is described.

3. SYSTEM TRADE-OFFS

3.1 The Role of Aircrew

In a modern military helicopter, the aircrew play a fundamental part in the operation of the aircraft as an effective total mission system. Their tasks fall broadly into two categories:

- piloting;
- tactical management.

Although traditional piloting tasks are vital, particularly in the NOE regime, it is important to emphasize the latter role in view of the complexity of the systems likely to be on board future helicopters. The aircrew represent the natural focus for the information flow within the aircraft, and will build up a tactical picture of the military situation as it affects them. This may require interpretation of information available over a tactical data network, aircraft/weapon status indicators, sensor and navigation displays as well as the view out of the aircraft window. The situational awareness of the crew is of primary importance not only to the effectiveness of the helicopter in fulfilling its role but also in ensuring its survivability. The timely provision of relevant information will be an important factor in enabling the crew to make key decisions concerning target acquisition, engagement, threat evasion, tactical route selection and signature minimisation.

The aircrew also have an important role in operating weapon systems. This is particularly true of the aiming process, which may require precise manoeuvring of the helicopter, together with target designation using manual systems or, in the future, head or eye-pointing systems.

Communication is another important element in the management of the helicopter. In general, the crew in an aircraft will communicate with:

- one another, ensuring that (in a multiple crew aircraft) they operate as a cohesive team.
- other helicopters in the group, enabling effective cooperative operations to be performed.
- other forces, for example ensuring route clearance and providing situation reports to the command base.

In general, the aircrew represent a vital component of the total system, enabling the considerable potency of military helicopters to be exploited optimally by the use of effective tactics.

3.2 Information Management

Over the next decade, the provision of tactical information is likely to be of critical importance for helicopters operating in various battlefield roles. As discussed in the previous section, ready access to current tactical information in the helicopter cockpit is likely to result in enhanced situational awareness and thus improved mission effectiveness and survivability.

The introduction of a tactical data network into battlefield helicopters raises several important integration issues. The aircrew have a considerable workload and it is therefore important that information from various sources is brought together and fused to present a single reliable picture of

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

the battle situation as relevant to the helicopter. This requires that any spatial and temporal ambiguities between information from the different sources are resolved to avoid confusion. For example, it is important to establish whether target information derived from on-board sensors, such as the thermal imager, relates to the same threat platforms as those represented in the tactical data communicated over the information network.

The presentation of all this information to the aircrew, requiring them to determine which data is of direct importance to them, imposes an unacceptable additional workload. It is therefore highly desirable that a degree of automatic information prioritisation, possibly based on threat potential or location, is achieved within each aircraft. This would ensure that aircrew are only furnished with that information which is currently relevant to the mission.

Finally, it is vital that information is displayed to the crew in a manner which can be readily assimilated. In a battlefield situation when operating NOE, helicopter aircrew require the capability to operate as much as possible looking out of the cockpit. Helmet-mounted displays (HMD), which, for example, offer the capability to present threat information overlaid conformally on the real world, support this "head-up, eyes-out" philosophy. However, the HMD is limited in the amount and type of information that can be effectively presented. The conventional multi-function head-down display provides a complementary medium, which enables such information as route plans and long range data to be shown as terrain-referenced overlays.

3.3 Weapons

In the future, a wide range of weapons, including cannon, free flight aerial rockets (FFAR), high velocity missiles and laser weapons, will be available for use by a helicopter both in an offensive role and in response to attack by a threat. The threats most likely to be encountered are ground-based mobile air defence units, shoulder-launched surface-to-air missiles (SAM) and other helicopters. As a result of the NOE tactics adopted by helicopters in the battlefield, man-portable ground-based threats will frequently be encountered at very short range and rapid deployment will be an important issue. Consequently, it may be that FFAR and missiles are less well suited to this situation.

In an anti-helicopter engagement, rapid manoeuvring to bring the threat within the weapon envelope is likely to be a critical factor. For bore-sighted weapons, the agility of the helicopter will be of greater importance than for turreted weapons, which have an inherent off-bore-sight capability and therefore require a combination of aircraft and turret manoeuvring to perform the aiming process. The use of off-bore-sight targeting systems (steerable sights, head or eye-pointing systems) will also contribute to the speed of response to a threat.

The time-of-flight of a weapon is also an important factor. The laser weapon, with an effective zero flight time, has a considerable advantage in this respect, alleviating the need for complex fire-control calculations. Furthermore, its inherent agility and lack of recoil give it great potential for rapid deployment. However, when operated from a platform with intrinsically high vibration levels, the problems of aiming such a system with the required precision to achieve appropriate terminal effectiveness are considerable.

For beam-rider, wire-guided, laser-guided or semi-active radar-guided missiles, time-of-flight is also important since it directly influences the period for which the helicopter must maintain line-of-sight to the target after firing. From an operational perspective, this affects the vulnerability of the aircraft to enemy weapons. Although autonomous, lock-before-launch, fire-and-forget missiles overcome this problem, the need to establish line-of-sight between missiles positioned on the weapon pylons and the targets leads to exposure of the helicopter during the lock-on and launch phases of an engagement. Again this can compromise the covertness of the aircraft.

From this brief discussion, it is evident that the effectiveness of different weapon systems will vary considerably with range, the degree of manoeuvre required and the circumstances of the engagement. Different weapons are likely to be optimal for different situations.

3.4 Other Sub-systems

Various other sub-systems contribute to the effectiveness of the helicopter as a weapon system. Of these, thermal imaging (TI) sensors are one of the most important since they are employed for three primary purposes (as illustrated schematically in Fig.1):

- As a reconnaissance sight;
- As a weapon aiming sight;
- As an integral component of a visually coupled system (VCS).

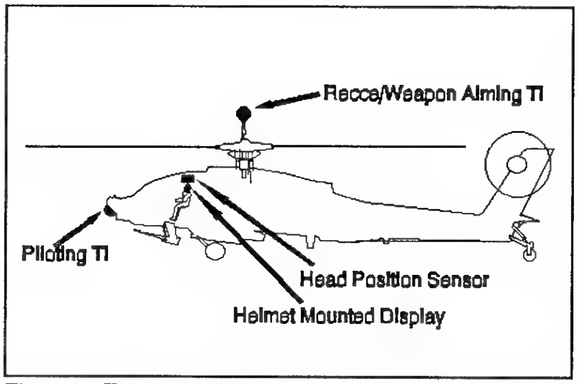

Figure 1 Thermal imaging sights on a generic helicopter

As a sighting system, the TI would be located high on the airframe, preferably in a mast-mounted configuration enabling the helicopter to exploit cover to remain covert and also yielding a full 360° field-of-regard. Used in conjunction with the armaments, the infra-red sensor potentially provides a means of aiming turreted weapons and has an inherent target acquisition capability, enabling designation of targets for guided missiles. For laser systems operating at IR wavelengths, the TI also affords the feedback for directing the beam onto the target.

Modern attack helicopters are increasingly using visually coupled systems (VCS) to give a day/night, all weather capability in the NOE environment. The basic system comprises a head-position sensor, a helmet-mounted display and an electro-optic imaging sensor (frequently a TI) mounted on a gimbal system. In operation, the imager is automatically pointed in the direction of the crewman's

head and the image projected on his HMD. On the AH64, VCSs are provided for both crew in the tandem seat aircraft, the imaging sensors being positioned in the nose. When flown operationally, the system has proved valuable in extending the conditions when helicopters can be employed. However, several problems remain, and the subject is an area of continuing research.

Another important class of sub-system is the Defensive Aids Suite (DAS), which assumes major significance in the survivability of the helicopter. In future rotary-wing aircraft, the system is likely to consist of a series of sensors, including laser and radar warning receivers and hostile fire and missile approach warners, together with countermeasures, which may include IR and radar jammers, chaff and decoy flares. In principle, on detecting a threat, it is possible to deploy appropriate countermeasures automatically, although crew intervention may be preferable in tactically sensitive situations. Furthermore, in a fully integrated system, the defensive weapon systems might also be aimed and activated automatically in response to threat warnings.

4. Studying Helicopter Systems Integration

In approaching the study of complex systems with multiple interactions, it is important to understand not only the technology issues and trade-offs but also the behaviour of the total system. A technique, well proven at the UK Defence Research Agency[1], is the use of mission simulators, based on graphics workstations, to provide an environment in which the platform, aircrew, mission systems and weapons can be assessed in a realistic operational context. The HOVERS facility[2] enables "multiple-man-in-the-loop" investigations to be performed in the NOE environment, allowing aircrew to become familiar with new technologies, while developing appropriate tactics to exploit the new capabilities.

4.1 The HOVERS mission simulator

The HOVERS (**H**elicopter **O**perational **V**isual **E**ngagement **R**eal-time **S**imulation) mission simulation facility is designed to allow detailed modelling of helicopter operational scenarios using high fidelity representations of aircraft systems. It enables realistic man-in-the-loop simulation of helicopter missions and uses state-of-the-art Silicon Graphics workstations to provide high fidelity representations of sensors, instruments and the outside world. Since its inception in 1993, the system has been used to provide advice to the UK Army Air Corps on future equipment options.

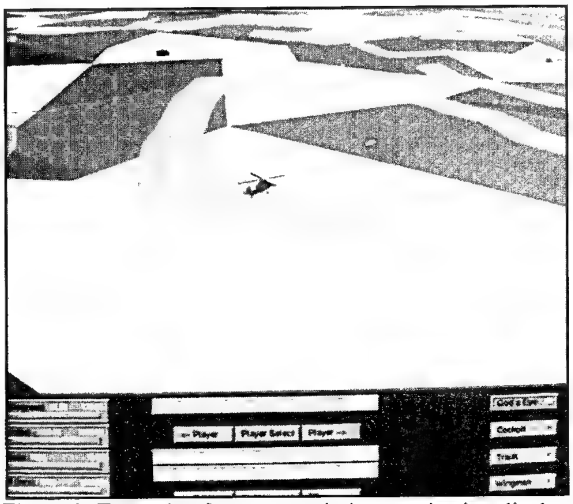

Figure 2 Example of a master mission monitoring display

The current configuration comprises 3 manned helicopters, each having 2 crew who can be seated either side-by-side or in a tandem arrangement. Additional computer-controlled forces, including other helicopters, main battle tanks, mobile air defence units and artillery, are also available to create a realistic battlefield environment.

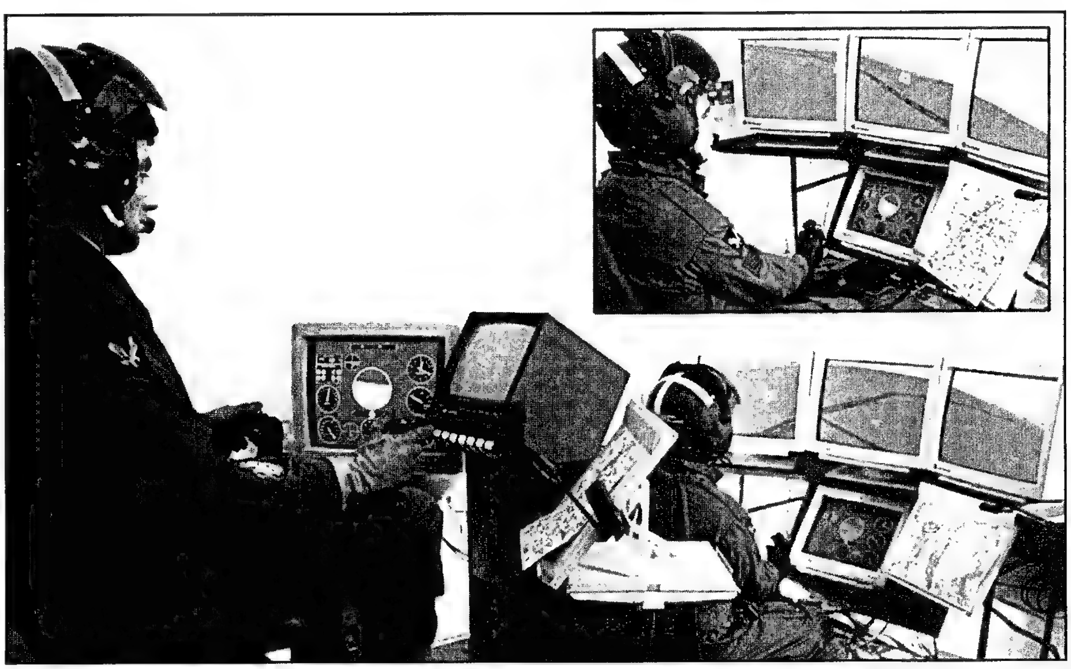

Figure 3 HOVERS tandem helicopter cockpit

Overall control and monitoring is achieved using additional workstations which provide reports of significant events such as missile firings and a master display such as the one shown in Fig.2.

The master display provides a 3-dimensional view of the battlefield, with the facility to show all combatants, missiles and terrain features in real time. Controls to vary the view and track specific combatants are also included, together with a logging facility which enables subsequent replay for tactical debriefing.

Each individual HOVERS station is configured with a position for a pilot and commander, as illustrated in Fig.3. The pilot flies the helicopter using conventional cyclic stick, collective lever and yaw pedals, his view of the outside world being provided by 3 graphics workstations. In a head-down location, an instrument panel provides him with all necessary flight and mission information. The commander has a display (illustrated in Fig.4) from a stabilised infra-red sight, which he can control using a joystick and pistol grip. The sight also enables him to fire command-to-line-of-sight or fire-and-forget missiles and operate a laser rangefinder.

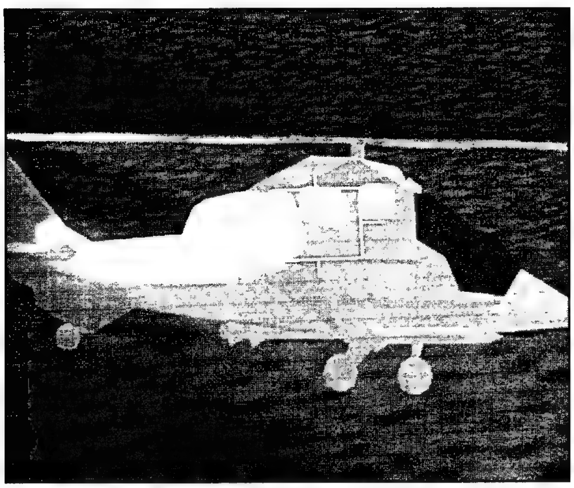

Figure 4 IR display of a generic HOVERS helicopter

Special features of the HOVERS simulation include dynamic modelling of IR and radar signatures in real-time, an object-oriented approach[3] which enables combatants to be modified interactively at run time, a comprehensive Defensive Aids Suite (DAS) and a realistic threat environment.

The multiple man-in-the-loop approach allows the important areas of crew communication, tactical interaction and cooperative operations to be addressed effectively. Perhaps even more significantly, it provides an environment in which tactics and new capabilities derived from emerging technologies can be developed together.

4.2 Example application

A typical issue affecting helicopters operating NOE in a high threat environment is that of the trade-off between command-to-line-of-sight (CLOS) and fire-and-forget missiles for self-defence. In order to address this on HOVERS, a pair of battlefield helicopters would be configured with each of the weapon options in turn and flown by military personnel. Full military orders would be given to the crews and a series of missions performed, involving both friendly and enemy ground forces and a further man-in-the-loop helicopter representing the enemy air threat. Routes would be carefully defined to ensure appropriate interactions between opposing forces and detailed data describing the combat would be logged for later analysis.

It might be anticipated that the issues emerging from such a comparison might include:

- the differing off-boresight capability;
- the difference in constraints on aircraft manoeuvres during missile flyout;
- difficulties associated with achieving lock before launch;
- differences in the requirements for inter-crew communication prior to and after launch.

It is likely that all these factors would influence the mission effectiveness and survivability of the aircraft and these parameters, together with range and time information could be assessed directly from the logged data. Application of statistical tests and use of structured questionnaires would enable the comments of the military aircrew to be noted, together with objective measures of operational performance.

5. CONCLUDING REMARKS

This paper has described some of the system trade-offs and integration issues associated with the next generation of military helicopters operating NOE in the battlefield. The interactions between weapons, sensors, aircrew and the platform itself are complex and it is important to address not only the technology issues and trade-offs but also the behaviour of the total system in appropriate operational contexts. The "total system" concept is vital to achieving an understanding of the helicopter as an integrated weapon system. The "multiple-man-in-the-loop" workstation-based approach to the study of helicopter systems integration has proved a significant step towards gaining an insight into the potential of the future battlefield helicopter.

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7. GLOSSARY

DAS	Defensive Aids Suite
DRA	Defence Research Agency
FFAR	Free Flight Aerial Rockets
HMD	Helmet-Mounted Display
IR	Infra-Red
NOE	Nap-Of-the-Earth
SAM	Surface-to-Air Missile
TI	Thermal Imager
UN	United Nations
VCS	Visually-Coupled System

A Highly Reliable, High Performance Open Avionics Architecture for Real Time Nap of the Earth Operations

Richard E. Harper
The Charles Stark Draper Laboratory
555 Technology Square, MS 62
Cambridge, MA 02139

Carl Elks
US Army CECOM
Joint Research Projects Office
NASA Langley Research Center
Hampton, Virginia 23681-0001
MS 130

Summary

Terrain-Following/Terrain-Avoidance (TF/TA) and Nap-of-the-Earth (NOE) helicopter flight will rely on high-throughput digital processing to perform flight-critical functions. Guidance and trajectory commands generated by these functions can be fed to a fly-by-wire Flight Control System (FCS), which is also flight-critical. Additional functions which might be performed by an integrated system include display imagery and Pilot Vehicle Interface, sensor and actuator management and processing, Aircraft Survivability processing, air data processing, weapons management, CNI processing, and engine control. Successful execution of this suite of functions requires a digital system which has both high performance and reliability, while a high sortie availability is extremely desirable because of its strong effect on fleet life-cycle costs. However technologically feasible, such a system is of no use if it is too expensive to produce, procure, maintain, and upgrade.

To address these needs the Army Fault Tolerant Architecture (AFTA) was designed and constructed. This computer is a militarized version of the Fault Tolerant Parallel Processor (FTPP) developed by Charles Stark Draper Laboratory (CSDL). AFTA is a hard-real-time Byzantine resilient parallel processor. It supports testability and redundancy management strategies which permit the reconfiguration of processing sites to enhance sortie availability and mission reliability. It is composed largely from Non-Developmental Items (NDI) to reduce the development risk and cost and facilitate upgrades.

1.0 Introduction

Military rotorcraft that operate in hostile threat environments have a critical requirement for low-level flight penetration capability in night time and adverse weather conditions. Presumably, low flying rotorcraft that can fly and maneuver close to the earth's surface, utilizing the surrounding land terrain, vegetation, and man-made objects will be able to minimize the risk of detection, thus increasing the likelihood of mission effectiveness and survivability. In addition, the low-flying rotorcraft must be able to identify and avoid hazardous areas, and maneuver away from them. This type of flight operation is often called Terrain Following/Terrain Avoidance, Nap of the Earth Flight, or simply TF/TA NOE flight. As expected, low altitude TF/TA piloting coupled with the demands of tactical missions produces a large amount of situational data that can easily overwhelm a two man rotor craft crew. To alleviate TF/TA NOE flight management burdens, computer aided flight planning integrated with full authority digital flight control offers the most promise for achieving automated TF/TA guidance and control. More importantly, the processing of critical flight control information at low altitudes with short reaction times is life-critical and mission critical necessitating a ultra-reliable/high throughput computing platform for dependable service for flight control, fusion of sensor data, route planning, near-field/far field navigation, and obstacle avoidance operations.

The traditional approach to meeting stringent requirements for military systems has been to design, build and validate a system from scratch to military specifications. Although such systems can be custom-tailored to meet the desired requirements, the design and validation cost makes them very expensive. The total design and validation time for such systems is also so long that by the time such systems are fielded they are obsolete. Also, because they are custom tailored, the effort involved in upgrading them can be as much as the original development effort. Leveraging of Commercial-Off-The-Shelf (COTS) technology and products as well as use of Non-Development Items (NDI) already designed and validated (for commercial or military applications) can reduce the system cost, reduce the time to field, facilitate upgrades, and generally provide state-of-the-art technology at a much more affordable price.

A system architecture called the Army Fault Tolerant Architecture (AFTA) has been designed and implemented to provide the desired attributes for the TF/TA NOE applications while minimizing the overall life-cycle cost of designing, building and maintaining such a system. The AFTA architecture provides the means for interconnecting COTS and NDI hardware elements such as workstations, processors, networks, I/O elements, etc. into a unified redundant system architecture that provides orders of magnitude higher throughput, reliability, survivability, and availability than any constituent component could provide by itself. AFTA-based system can host commercial operating systems such as the many variants of UNIX,

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POSIX-compliant standard operating systems, Ada run time systems, and others. AFTA provides appropriate primitives to schedule redundant tasks under these operating systems to meet the required hard real-time deadlines. This paper describes the TF/TA NOE applications requirements, AFTA architectural theory, hardware and software architectures, analytical models, and runtime performance measurements of the Dynapath algorithm hosted on the AFTA.

2.0 Application Requirements

The following functions might be performed by AFTA in the helicopter TF/TA/NOE mission.

TF/TA/NOE
Threat Avoidance/Engagement
Mission Planning
Guidance
Navigation
Vehicle Control
Sensor Management and Processing
Communications Management
Display Management

TF/TA/NOE flight requires the successful execution of the flight control system, very near-field planning, near-field planning, trajectory generation, far-field navigation, sensor management, navigation, and display functions. Because of the disastrous ramifications of losing TF/TA/NOE capability while flying at 100 knots 20 feet off the ground at night in the mountains, it may be safely assumed that most if not all of these functions are flight-critical.

Table 1 summarizes the TF/TA/NOE/FCS requirements obtained from a requirements acquisition conducted during the AFTA Conceptual Study. The requirements acquisition is continuing throughout the AFTA development. From the data available to date it has been difficult to arrive at a throughput estimate, it being far easier to determine the number of processing sites required to execute a given function. Therefore we have simply listed the processor count as obtained from the requirements acquisition. It is expected that, for a number of reasons, the processor count indicated in Table 1 provides a throughput that vastly exceeds that needed by the application. Therefore for the purpose of this paper, we shall proceed under the assumption that a smaller number of processing sites, say 6, are needed to execute the application. The AFTA modeling suite is parameterized on the number of processing sites–therefore this assumption is easily changed.

Throughput
1 TF/TA/NOE 680x0 3 Pilot-Vehicle Interface 680x0s 2 imagery R3000s 2 Flight Control System 680x0s 1 Flight Control System I/O 680x0
Total of 9 processing sites
I/O
200 Bytes in, ≈20 Bytes out at 50 Hz 128 Bytes in/out at 8 Hz 298 Bytes in/out at 4 Hz 128 Bytes in/out at 1 Hz
Aggregate bandwidth of 13,344 bytes/sec (0.107Mbit/sec) required
Criticality
Flight Critical

Table 1. Helicopter TF/TA/NOE/FCS Requirements Summary

2.1 Route Planning

Numerous solutions approaches to route planning and optimization have appeared in the scientific literature recently[Pek88],[Men91],[Due88],[Jun91].
Specifically, three distinct methods were evaluated by NASA Ames Research Center recently as plausible approaches to route planning, these are: (1) Discrete dynamic programming , (2) Simulated Annealing methods, and (3) Optimal control methods. Of the three methods, a route planner based upon dynamic programming techniques, called Dynapath [Pek88] was selected to form the basis of a computational TF/TA NOE workload for the AFTA. Methods two and three have not been ported to the AFTA at this time, so they will not be discussed any further.

Dynamic programming methods, like Dynapath, try to produce a globally optimal trajectory or route via a directed search as constrained by a cost function. In principle, this is accomplished by constructing a tree structure of the possible lateral or vertical discretized path segments that the aircraft can follow for N seconds (e.g. 3 to 5 seconds). At set points, called nodes, decisions are made about the optimality of possible future path segments leaving that node. Paths emanating from a node are chosen in a way that satisfies the constraints to the cost function. To reduce search space, pruning is used to reduce the size of the search tree when the number of possible path segments becomes large. Again, decisions about pruning the search tree are made in a way that favors forward progress of the aircraft from the reference path. This procedure is repeated until an entire patch length is searched. A patch length is a linked aggregate of paths segments. Finally, an optimal patch length that has the lowest cost is chosen from the many path segments.

Also, most dynamic programming solutions apply a spatial coordinate discretization of the terrain data map before performing a systematic search for the optimal trajectory [Men91]. Therefore, the route in some discretized interval, is composed of many adjacently connected straight-line segments. As the terrain becomes more irregular, the number of discretization interval increases, in a effort to generate a smooth trajectory for the rotor craft as it attempts to maneuver through the uneven terrain. As expected, this increase in the number of discretization intervals directly corresponds to an increase in computational complexity [Men91].

The computational cost is:

$O[(n + 1)^2 - 1]$

where n is the number discretization

intervals.

Thus, choosing the correct spatial discretization parameters and pruning parameters can have significant impact on the computation requirements to generate a solution. What this suggests, is that for difficult route planning missions which include uneven terrain, with many goal points and waypoints, high throughput is required to solve the equations for optimal or near-optimal trajectories in real-time.

2.2 Dynapath Application

For our purposes, a brief overview of the Dynapath will suffice, however an in depth description of Dynapath can be found in reference [Pek88]. Dynapath uses digital map data, the current vehicle state (e.g., position, velocity), vehicle dynamical constraints (e.g., maximum rate-of-bank, load), a set of waypoints over which the vehicle must fly, desired trajectory constraints (e.g., setpoint altitude), and other information to construct a trajectory which meets all these constraints and requirements. The generated trajectory is then presented to the pilot on a head-up-display (HUD) in a simple-to-use "highway-in-the-sky" format, which the pilot may follow. The Dynapath functionality is likely to be safety-critical, especially in low-visibility conditions.

The Dynapath TF/TA application was hosted on a quadruply redundant AFTA environment. Figure 1 shows the major components of the demonstration. At the left of the figure, Dynapath resides on the quadruply redundant AFTA, along with LynxOS and the Network interface software described elsewhere in this report. Dynapath communicates with vehicle dynamical simulation software (Helsim) and the HUD symbology generation software running on a Silicon Graphics (SG) workstation using Ethernet-based TCP/IP. The out-of-window view of the terrain, the Dynapath-generated highway-in-the-sky symbology, and other HUD symbology are presented on a high-resolution graphics monitor connected to the SG.

Periodically, Dynapath transmits a request for vehicle state from the helicopter simulation. When it receives a state update from the simulation, Dynapath calculates a new commanded trajectory segment and transmits the new trajectory segment description to the symbology generation software. The "pilot" views the terrain and Dynapath symbology and provides cyclic and collective commands to the helicopter simulation via a mouse and joystick as she attempts to follow the commanded trajectory.

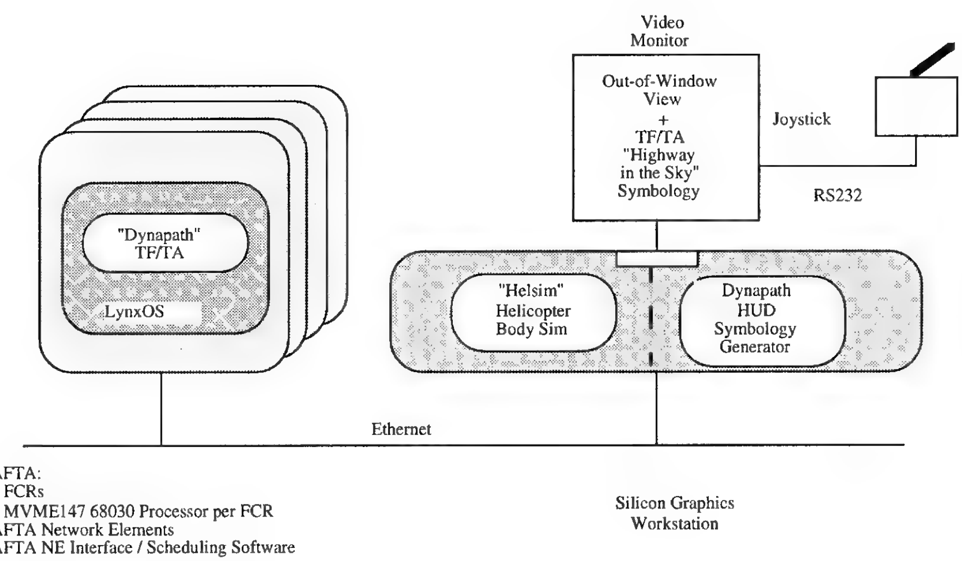

Figure 1. Architecture of Dynapath Demonstration

3.0 AFTA Architectural Theory

Due to the stringent real-time requirements of the TF/TA application, computation cannot be suspended for more than a few milliseconds when a component fails. Fault effects must be masked until recovery measures can be taken. A majority voting architecture with a triplex-or-higher level of redundancy masks errors and provides spares to restore error masking after a failure. Use of redundancy, of course, is quite common in critical systems. However, managing that redundancy is supremely important.

Redundancy alone does not guarantee fault tolerance. The only thing it does guarantee is a higher fault arrival rate compared to a non redundant system of the same functionality. For a redundant system to continue correct operation in the presence of a fault, the redundancy must be managed properly. Redundancy management issues are deeply interrelated and determine not only the ultimate system reliability but also the performance penalty paid for fault tolerance. A fault-tolerant computer can end up spending as much as 50 percent of its throughput managing redundancy [Pal86].

As a first step in addressing this issue, we partition the redundant elements into individual fault containment regions. An FCR is a collection of components that operates correctly regardless of any arbitrary logical or electrical fault outside the region. Conversely, a fault in an FCR cannot cause hardware outside the region to fail.

To form a fault containment boundary around a collection of hardware components, one must provide that hardware with independent power and clocking sources. Additionally, interfaces between FCRs must be electrically isolated. The isolation should be robust enough to tolerate a short to the maximum voltage available in the FCR. Depending on the application, this may be 5V or 28V DC, 115V AC — or even higher in a HERF/EMI (high-energy radio frequency/electromagnetic interference) environment.

Some applications also require tolerance to such physical damage as a weapons hit or flooding. In those cases, FCRs must also be physically separated, typically done by locating redundant elements in different avionics bays on aircraft or in compartments separated by bulkheads in underwater vehicles.

Due to all these requirements, it is impractical to make each semiconductor chip, or even a board, an FCR. A realistic FCR size is that of a whole computer, also called a channel in the avionics parlance. A typical channel contains a processor, memory, I/O interfaces, and data and control interfaces to other channels. If the FCR requirements are enforced rigorously, one can argue that random hardware component failures in FCRs constitute independent and uncorrelated events. This is an important underpinning of the analytical models used to predict the probability of failure of these systems.

Although an FCR can keep a fault from propagating to other FCRs, fault effects manifested as erroneous data can propagate across FCR boundaries. Therefore, the system must provide error containment. The basic principle is fairly straightforward: "voting planes" mask errors at different stages in a fault-tolerant system. For example, a typical embedded control application involves three steps: read redundant sensors, perform control law computation, and output actuator commands.

In an embedded application, an input voting plane masks failed sensor values to keep them from propagating to the control law. Internal computer voting masks erroneous data from a failed channel to prevent propagation to other channels. Output voting and an interlock mechanism prevent outputs of failed channels from propagating outside the computational core.

The interlock is a hardware device in each channel that can enable or disable the outputs of that channel. Only a majority of the channels can change the interlock state. Therefore, in triplex or higher redundancy level computers, the majority of channels can disable the outputs of a failed channel.

Finally, a voting plane at the actuator masks errors in the transmission medium that connects the computer to the actuators. The typical actuator is driven by multiple electrical or hydraulic inputs so that a majority of inputs can drive it to the correct position even when one of the inputs fails to its maximum value, or a "hardover failure."

Masking faults and errors obviates the need for immediate diagnostics, isolation, and reconfiguration. The application functions need not be suspended. The majority of channels can continue to execute these functions correctly and provide correct outputs. This approach meets the stringent real-time response requirements.

4.0 AFTA Hardware Architecture

The AFTA is based on the Fault Tolerant Parallel Processor (FTPP) architecture developed by Draper Laboratory. The FTPP architecture was conceived to satisfy the dual requirements for a computer system of ultra-high reliability and high throughput. To satisfy the first requirement, the FTPP is designed to be resilient to Byzantine faults. To satisfy the throughput requirement, the architecture includes multiple processing elements to provide parallel processing capability. For a detailed description of the FTPP the reader is referred to [Abl88], [Bab90a], [Har87], [Har88a], [Har88b], and [Har91].

The FTPP is composed of Non-Developmental Item (NDI) Processing Elements (PEs), Input/Output Controllers (IOCs), Power Conditioners (PCs), backplane/chassis assemblies, and specially designed hardware components referred to as Network Elements (NEs).

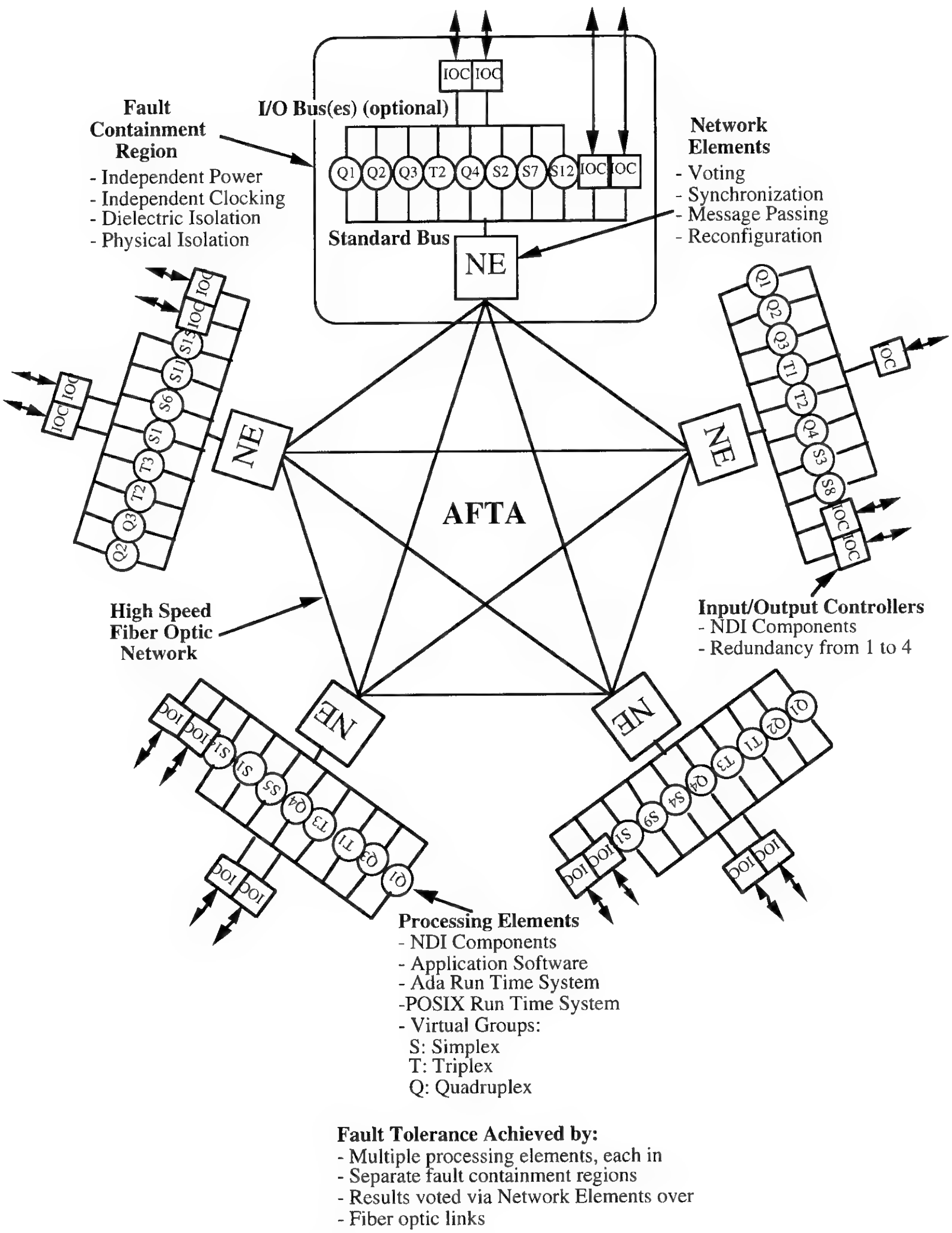

Figure 2. AFTA Physical Architecture

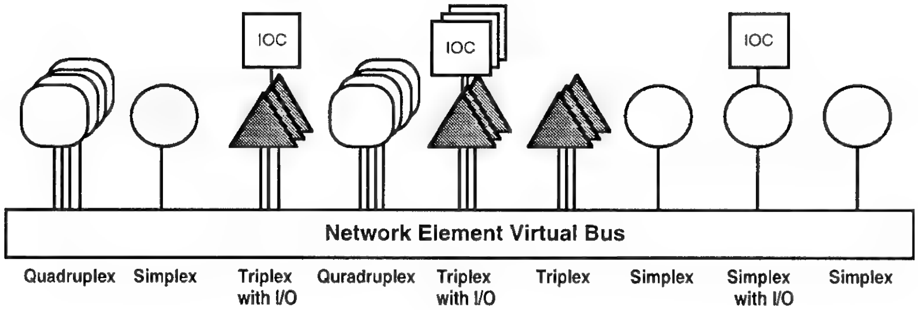

Figure 3. AFTA Virtual Configuration

A diagram of the physical AFTA configuration is shown in Figure 2. The AFTA cluster consists of 4 or 5 Fault Containment Regions (FCRs). A fault occurring in one FCR can not cause another FCR to malfunction; this is achieved by providing each FCR with independent sources of power, clocking, and dielectric and physical isolation. FCRs reside in Line Replaceable Units (LRUs). FCRs may either be distributed among several LRUs for damage tolerance or integrated into a single LRU if damage tolerance is not an issue. Each FCR contains an NE, 0 to 8 PEs, a PC, and 0 or more IOCs. A minimal AFTA configuration consists of at least four NEs and three PEs; a maximal system would consist of five NEs and forty PEs. Selection of the number of NEs and PEs for a given application is made according to performance, reliability, availability, and other engineering requirements.

Devices in an FCR are interconnected using one or more standardized backplane buses. Depending on the procuring organization, this could be the VMEbus, SAVA SBBUS, PIbus, Futurebus+, or some other bus. The NE's bus-dependent and bus-independent circuitry are intentionally partitioned such that changes in the FCR backplane bus only affect the former, allowing the AFTA concept to transition from one standards suite to another with minimal hardware redesign.

The NEs provide communication between PEs, keep the FCRs synchronized, maintain data consensus among FCRs, and provide dielectric isolation between the FCRs via fiber optic links. The NE implements the protocol requirements for Byzantine resilience [LSP82]. The NE is the only developmental hardware item in AFTA. To facilitate its design, simulation, fabrication, and reprocurement, the NE is described using VHDL.

Each PE consists of a processor, private RAM and ROM, and miscellaneous support devices, such as periodic timer interrupts. The PEs may optionally have private I/O devices, such as Ethernet, RS-232, etc. The processor may be either a general-purpose processor or a special-purpose processor for signal or image processing. Multiple processor types may coexist simultaneously and interoperate in an AFTA implementation.

The IOCs connect AFTA to the outside world, and can be any module that is compatible with the FCR standard backplane bus. Interfaces to communication networks such as the JIAWG HSDB and the AFTA Fault Tolerant Data Bus (FTDB) are also classified as IOCs. Alternatively, for maximum I/O bandwidth, multiple dedicated I/O buses may be used. Both options are shown in Figure 2.

To achieve fault tolerance, nonredundant PEs are grouped into Virtual Groups (VGs), depicted in Figures 2 and 3. Byzantine resilient triplexes and quadruplex VGs consist of three and four PEs, respectively. Virtual groups consisting of only one processing site are called simplexes. The ensemble of Network Elements provides a virtual bus abstraction connecting the VGs (Figure 3). This abstraction conceals the multiple NEs and their interconnect, replacing it with a simple bus-oriented abstraction.

5.0 AFTA Software Architecture

Operating systems that have been run on the FTPP include VRTX, VXWorks, LynxOS, IRIX, the XD Ada Run Time System, and custom kernels. Different Virtual Groups may run different operating systems in a given FTPP implementation. When an appropriate operating system for the application has been selected, porting a new operating system to the FTPP requires minimal effort. This paper briefly describes the Ada Run Time System and the LynxOS system.

The FTPP hardware and software have been designed to hide the hardware redundancy, hardware faults, and the distributed processing details from the applications programmer. A system configuration table specifies the mapping from tasks to VGs and from VGs to processors. This mapping is maintained by the operating system and is used to isolate the applications programmer from the underlying redundancy and distributed processing mapping.

FTPP is best viewed as a layered system. The top layer consists of the applications programs themselves. These are constructed by the application engineers with minimal regard for the parallel and redundant nature of FTPP. An important function of the FTPP System Services not typically accessible by the applications programmer is the Fault Detection, Identification, and Recovery (FDIR) service. FDIR detects the presence of

faults and initiates an appropriate recovery strategy, and is typically implemented as an application task.

The next lower layer consists of the FTPP System Services. This layer and its associated Application Programmer Interfaces (APIs) are intended to mask the complexity of FTPP's lower layers from the application programmer. Several services may be invoked by the application programmer through appropriate APIs; these include task scheduling, intertask communication, voting, and input/output. Multiple APIs can be concurrently resident on a Virtual Group in the FTPP, and are selected based on the needs of and compatibility with the intended application. The API resides on a COTS operating system, of which examples have already been given. Depending on the operating system, the Network Element Interface software may be implemented as inline calls directly accessing the Network Element, a device driver, or another appropriate mechanism.

At the next lower level of the logical hierarchy reside the COTS hardware platforms and the NDI interprocessor communication network hardware, known as Network Elements. At the lowest layer of interest reside the inter-NE communication links, which provide high-speed optical communication paths among the FCRs.

5.1 Task Scheduling

The AFTA supports two different styles of scheduling, each of which is suited for different application domains. The first, known as rate group scheduling, is suitable for task suites in which each task has a well-defined iteration rate and can be validated to have an execution time which is guaranteed to not exceed its iteration frame (the inverse of its iteration rate). The second style of scheduling, known as aperiodic scheduling, is necessary when the iteration rate of a particular task is unknown or undefined. Validation of the temporal behavior of such tasks may be difficult. In AFTA, aperiodic tasks are not allowed to perturb the critical timing behavior of rate group tasks. The AFTA supports task suites consisting of a mixture of rate group scheduling and aperiodic scheduling.

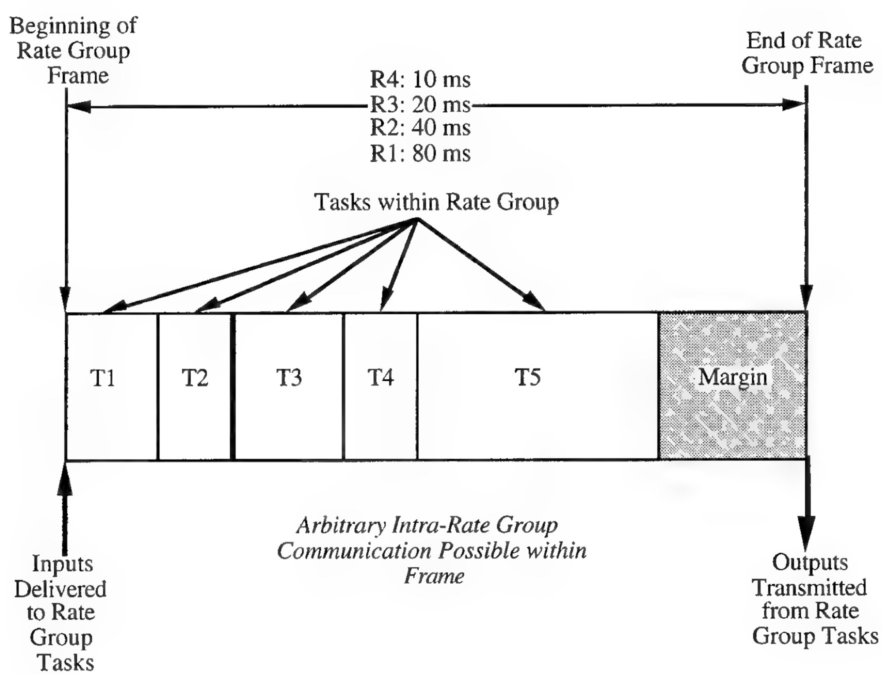

Figure 4. Rate Group Frame-Programming Model

5.2 AFTA Ada Run Time System

5.2.1 Rate Group Scheduling

An operating system which has been used on the AFTA is the XD Ada RTS enhanced by Draper. One of these enhancements is a multi-rate group scheduler layered upon the XD Ada run time executive. In such a paradigm tasks executing on each VG in the AFTA are characterized by an iteration rate. In the AFTA, these rates are nominally 100, 50, 25, and 12.5 Hz, corresponding to rate group identifiers R4, R3, R2, and R1, respectively. A rate group frame duration is the inverse of the rate group iteration rate; thus the R4, R3, R2, and R1 frames are 10, 20, 40, and 80 ms in duration, respectively. The frequencies and number of rate group frames are readily changed as the application dictates. Frames executing on different VGs in the AFTA need have no particular phase relationship with each other, although a desired phase relationship among certain frames may be enforced in some applications to reduce contention for the NE. Within a particular rate group frame, tasks of that rate group are executed using a non-preemptive static schedule. The exact time of execution of a particular task in the rate group frame will be in general unknown to the application programmer. Instead, AFTA guarantees that all tasks within a rate group will be executed in the order specified by the application programmer sometime within the appropriate rate group frame. Figure 4 illustrates the basic idea of a rate group.

5.2.2 Aperiodic Scheduling

Aperiodic tasks are executed after all rate group tasks have been executed. There may be several aperiodic tasks running on a VG. Messages and I/O operations emanating from aperiodic tasks are handled differently from those emanating from RG tasks. When an aperiodic task wishes to transmit a message or execute an I/O operation, the message is appended to an asynchronous queue specific to that aperiodic task. On every frame, the Dispatcher task performs a series of exchanges regarding the status of this queue to determine if all copies of the aperiodic task have requested the message transmission, or if a majority of the copies have requested the transmission and a suitably long time-out interval has expired such that the minority of the copies can be presumed to be faulty. If either of these conditions are met, the Dispatcher transmits the message.

The aperiodic task time-out calculation is based on the amount of processor time the task consumed since its last synchronization act. This quantity defines the elapsed execution time of the task. All copies of the task may not have identical elapsed execution times, so a fault tolerant algorithm must be employed to exchange and agree upon a valid execution time. Given that all copies of the Dispatcher agree upon a valid elapsed execution time, the time-out may be calculated if the amount of skew buildup per processor time unit is known.

Avg. Time (μsec)	% of Minor Frame	Stand Dev. (μsec)	Max. Time (μsec)	Min. Time (μsec)
141	1.4 %	14	168	130

Table 2. Execution Time for RG Dispatcher - First Part

Avg. Time (μsec)	% of Minor Frame	Stand Dev (μsec)	Max. Time (μsec)	Min. Time (μsec)
1268	12.7 %	404	2134	549

Table 3. Execution Time for RG Dispatcher - Second Section

Avg. Time (μsec)	% of Minor Frame	Stand Dev (μsec)	Max. Time (μsec)	Min. Time (μsec)
84	.08%	0	84	84

Table 4. Execution Time of the Local FDIR Task

Task	Avg. Time (μsec)	% of 10 msec Minor Frame
IH (Scoop)	653	6.5 %
RGD -1	141	1.4 %
RGD-2	1268	12.7 %
FDIR	68	0.7 %
TOTAL	**2130**	**21.3 %**

Table 5. Example Ada Operating System Overheads

5.2.3 Intertask Communication

All communication to tasks within a rate group, whether from input devices, the network elements, tasks executing in other rate groups on that VG, or messages emanating from other VGs in the AFTA, is delivered and made available to the rate group tasks at the beginning of their rate group frame, assuming it was sent in time to be received by the recipient VG before the frame boundary. All communication emanating from tasks within a rate group, whether sent to output devices, the Network Elements, tasks executing in other rate groups on that VG, or other tasks executing on other VGs, is queued within the rate group frame and transmitted at the end of that rate group frame. The single exception to this rule is made for non-preemptible R4 tasks, which can send and receive messages at any time.

5.2.4 Ada Run Time System Performance Measurements

To quantify the fault tolerance and Ada operating system overhead, various tasks were probed to measure their execution time. The objectives of this process were to empirically measure the system overhead, to develop analytical models which allow prediction of the performance measures of various system configuration and workload scenarios, and to facilitate identification and rectification of performance bottlenecks extremely early in the operating system development process. The results presented in this section quantify OS functions occurring within each minor frame of the scheduler. These measures can be divided into four parts. First is the overhead associated with the interrupt handler that executes twice during each minor frame. The second quantifies the execution time of both parts of the Rate Group Dispatcher. The third data set summarizes the performance of the I/O tasks. The fourth part comprises the overhead due to the FDIR task. The final group consists of other overheads associated with the operating system, including queuing and retrieving messages and context switching. The performance measurements presented in this paper were taken on an early version of the FTPP Ada Operating System running on a 20 MHz 68030-based Motorola MVME147S-1 Processing Element. Caches and compiler optimizations were turned on. These overheads are summarized in Tables 2 through 5.

5.3 AFTA LynxOS Operating System

In the past year the AFTA's open system characteristics were extended to include its operating system and software. To achieve this objective, the AFTA Network Element was integrated into a POSIX-compliant operating system. The utility of the resulting system was demonstrated by rehosting and executing the Dynapath application on the AFTA.

Several POSIX-compliant kernels were evaluated via vendor presentations and literature surveys. LynxOS was selected for detailed evaluation and demonstration. The AFTA NE was installed into the LynxOS environment. LynxOS / UNIX-compatible device drivers were written to allow application programs to access the NE, and a simple Application Programmer Interface was implemented to allow application programs to perform interchannel exchanges and synchronization. The Dynapath TF/TA algorithm was acquired from the Army and demonstrated in real-time on a quadruply redundant AFTA VG. Fault injections (e.g., channel resets and link disconnections) were performed to evaluate performance in the presence of faults.

5.3.1 Fault Tolerance Overheads in the LynxOS System

The Dynapath application is an iterative process having a period of approximately 3 seconds during routine operation. Every 3 seconds Dynapath executes three Ethernet transmissions, each of which requires one interaction with the NE. This interaction performs a NE device driver "ioctl" which requests an NE exchange at the next frame boundary.

In the LynxOS system, frame boundaries are generated by a 25 Hz timer interrupt onboard the processor. The timer interrupt service routine (ISR) contains the code to synchronously access the Network Element on behalf of the application tasks as well as to synchronize the VG. The time required to process this ISR contributes to the temporal overhead due to fault tolerance.

When Dynapath executes on a nonredundant computer system requiring no cross-channel exchanges, it can read Ethernet input and write Ethernet output immediately. However, when redundant operation is required, the inputs and outputs must go through the NE device driver. Because the NE interactions synchronize the redundant instantiations of Dynapath, the time required to wait for the slowest instantiation of Dynapath to request the exchange constitutes the I/O latency due to fault tolerance. Finally, the FDI function accesses the driver's internal state structure and copies the relevant data to the area provided by the caller. The time consumed by the FDI function is another overhead due to fault tolerance.

The total overhead due to fault tolerance for the Dynapath application is the sum of the overheads due to the timer ISR, the I/O latency, and the FDI functions. These data are summarized in Table 6.

6.0 Protection Against Common Mode Faults

The Achilles' heel of redundant fault tolerant computers is their vulnerability to common mode faults. A common mode fault is defined as one that affects multiple fault containment regions nearly simultaneously and is generally caused by a common cause such as lightning, software bug, hardware design fault, etc. The probability of a system failure due to common mode faults can be reduced significantly by reducing the incidence of design errors.

By using commercial-off-the-shelf (COTS) or Nondevelopmental Item (NDI) hardware, software, power supply modules, etc., one can leverage the

industry's huge investment in the testing and verification of components, essentially having others perform fault removal for free. The tradition in the industry for building critical digital systems is just the reverse. Almost invariably, the processors, memories, input/output controllers, operating system, and other system software is point-designed from scratch for a specific program, complete with brand new specification and design flaws. In our view this is analogous to beginning the construction of a new aircraft by prospecting for aluminum, titanium, and molybdenum deposits. In parallel, the laws of metallurgy, aerodynamics, structures, propulsion, and controls would be developed. These endeavors would eventually culminate in a flight vehicle. Fortunately, in these fields, unlike in critical digital systems, one selects from various handbooks airfoil shapes, spars and structural elements, alloys, etc. with well-characterized behavior over their expected operating ranges. We believe that it is high time for critical digital systems design methodology to attain this level of maturity.

Use of COTS/NDI hardware and software goes hand-in-hand with conformance of the design to commercial, military and/or de facto standards. A number of standards have been developed for the design of computer systems. Although the primary motivation for the development of standards is ease of interoperability, logistics, maintainability, reduced cost, and so on, one of the side benefits of using standards is the reduction of design errors. Widely-used standards usually result in detailed, precise, and stable specifications that can be adhered to in the design phase and, over time, verified against in the verification phase. Design errors due to ambiguous or changing specifications can be substantially reduced by the use of standards.

7.0 The Role of Standards in AFTA

The AFTA architectural concept is intended to be independent of prescriptive engineering standards which may apply to various applications. The ability to comply with differing standard suites without belying the validity of the AFTA architectural concept is indeed one of the strong points of the AFTA architecture, and is intended to give it a degree of universal applicability. Given AFTA implementation is constructed under due compliance with the standards asserted by the procuring organization. Standards may exist singly or may be aggregated into suites, and may apply to commercial, military, space, and other applications. For AFTA, we are primarily interested in existing or emerging standards which apply to military applications. Standard suites may include backplane buses, Instruction Set Architectures (ISAs), programming languages, interconnection network hardware and topologies, physical dimensions, connectors, communication protocol stacks, operating system services, and development, testing, and documentation procedures.

Standards assist in fixing unknown design parameters, thus removing many uncertainties. This in turn allows educated estimations of critical system parameters at an early enough stage in the design to detect and rectify potential problems. The use of standards implies the existence of a large body of NDI AFTA building blocks such as processors, input/output devices, interfaces, and software. This results in the potential for low cost of prototyping and procurement, while the components' maturity reduces the probability of design flaws. The availability of mature standards-compliant components substantially reduces the risk, schedule, and cost involved in utilizing them in AFTA. As higher performance, lower cost, more reliable, etc. standards-compliant components are developed, AFTA can be upgraded, thus leveraging inevitable trends in microelectronics technology. AFTA's use of standard interfaces and modules results in what is commonly referred to as an "open system."

Function	Time Required	Frequency	Overhead
Timer ISR	1.57 msec (no faults) to 3.73 msec (uncompensated fault)	25 Hz	3.9% to 9.3%
I/O Latency, per exchange	5 msec (minimum) to 22.5 msec (average) to 45 msec (worst case)	3 exchanges every 3 seconds	0.5% to 2.3% to 4.5%
GET_SYNDROME ioctl	60 μsec	25 Hz	0.15%
CLEAR_SYNDROME ioctl	60 μsec	25 Hz	0.15%
Total Overhead	**4.7% (Min.) to 6.5% (Avg.) to 14.1% (Max.)**		

Table 6. Total Overhead for Dynapath Application

8.0 Analytical Models

Several quantitative models have been developed for analytically evaluating AFTA. These include models for delivered throughput, delivered intertask communication bandwidth and latency, delivered input/output bandwidth and latency, reliability and availability under two typical AFTA redundancy management policies, weight, power, volume, and Life Cycle Cost (LCC). The inputs to these models come from MIL-HDBK-217E failure rate data, empirical test and evaluation, experience with prior FTPP prototypes, and other sources. For convenience sake, it is assumed in the sequel that all VGs have identical redundancy levels.

Table 7 displays the throughput (in MIPS) delivered to the application as a function of the number of PEs in AFTA, and the redundancy level of the VGs into which the PEs are grouped. The delivered throughput is defined to be the raw throughput minus the FDIR and operating system overheads. Based on prior experience, the analytical results presented in this paper were generated assuming that this overhead is equal to 20%–a more accurate estimation of this overhead will be made as detailed design and fabrication of AFTA progresses. A homogeneous AFTA containing PEs having a raw throughput of 20 MIPS (e.g., 68040- or R3000-class) is modeled. The delivered throughput does not account for the inefficiencies incurred in mapping a parallel computation onto the AFTA's multiple VGs. Therefore it represents an upper bound on the throughput available to the application.

Figure 5 illustrates the probability of catastrophic AFTA failure as a function of delivered throughput and the redundancy level of the VGs into which the PEs are grouped. The analysis assumes that AFTA is executing a one-hour mission in a rotary-winged aircraft. Abscissa values are proportional to the number of PEs in the AFTA (which may range from 3 to 40) divided by the VG redundancy level, times the delivered throughput per VG as computed above. The curves labeled with a "-4" suffix refer to an AFTA comprising 4 FCRs, and those labeled with a "-5" refer to an AFTA comprising 5 FCRs. The outlined area represents the envelope in performance and reliability space that a mixed redundancy AFTA configuration may explore.

From the throughput requirements one may determine the number of VGs required to perform the mission's functions. From the reliability models one may determine the minimum redundancy level these VGs must possess at sortie to meet the mission's reliability requirements. If these VGs are not available at sortie due to faults, then the vehicle can not sortie–therefore one is tempted to add spares to increase mission availability. Figure 6 shows the effect on mission availability of adding spare PEs in each FCR and spare FCRs to an AFTA, assuming that six VGs are needed to sortie. The hiatus interval is assumed to be 23 hours at Ground, Fixed failure rates. The curves labeled with a "-4" suffix refer to a configuration containing no spare FCR, while the curves labeled by the "-5" suffix refer to configurations containing a spare FCR. For the given model input parameters, addition of more than a single spare PE per FCR does not significantly enhance availability. Addition of a spare FCR helps more, while the combination of one spare PE per FCR and one spare FCR greatly enhances availability. These analytical results are used to select a sparing policy commensurate with the vehicle availability requirements.

The VG redundancy level affects the LCC in several ways. Increasing redundancy reduces the probability of catastrophic AFTA, and hence vehicle, loss; this clearly is an event having significant costs associated with it. On the other hand, increased redundancy increases procurement, maintenance, and spares cost. Adding spares increases mission availability, thus requiring the purchase of fewer vehicles to achieve a given sortie rate. On the other hand, increased spares also increases procurement, maintenance, and spares cost. An LCC model has been constructed for the AFTA helicopter mission which takes into account cost due to unavailability, vehicle and AFTA procurement cost, cost due to maintenance man-hours, cost due to spares and refurbishment parts, and cost due to unreliability. Table 8 illustrates the variation of the overall fleet LCC with VG redundancy level for a fleet of 100 vehicles, each costing \$6M. It is assumed that 6 VGs are needed to perform the mission's functions. For the simplex VGs, the life cycle cost is huge because of the relatively frequent loss of vehicles due to failure of AFTA. Clearly no one would field such a system. In the case of redundant VGs, both have a negligible cost associated with in-flight failures. The triplex has a lower LCC than the quadruplex VGs because their LCCs are dominated instead by procurement, maintenance, and spares costs. Therefore, in the given example, a triplex system is more cost-effective since these costs are lower for it. It should be borne in mind that these are representative results only and depend strongly on constituent costs such as the cost of in-flight failure.

Table 9 shows the AFTA weight, power, and volume as a function of the number of PEs and FCRs. It is assumed that AFTA is composed of JIAWG-standard single-slot SEM-E LRMs and LRUs. The average power dissipation per LRM is assumed to be 15W, with a power supply efficiency of 90%.

# PEs	# Simplex VGs	Delivered Throughput	# Triplex VGs	Delivered Throughput	# Quad VGs	Delivered Throughput
5	5	80.00	1	16.00	1	16.00
10	10	160.00	3	48.00	2	32.00
15	15	240.00	5	80.00	3	48.00
20	20	320.00	6	96.00	5	80.00
25	25	400.00	8	128.00	6	96.00
30	30	480.00	10	160.00	7	112.00
35	35	560.00	11	176.00	8	128.00
40	40	640.00	13	208.00	10	160.00

Table 7. AFTA Delivered Throughput (MIPS) vs. Number of Processing Elements

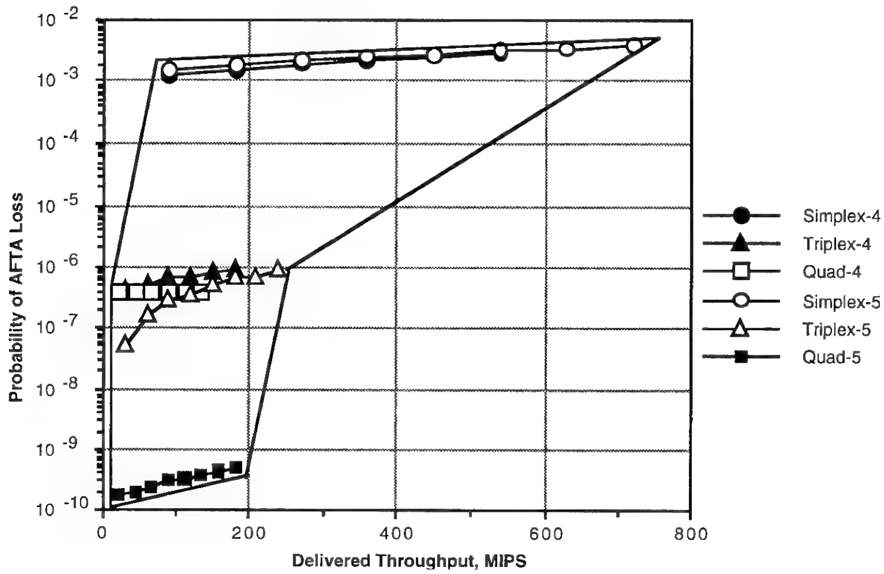

Figure 5. AFTA Loss Probability vs. Delivered Throughput

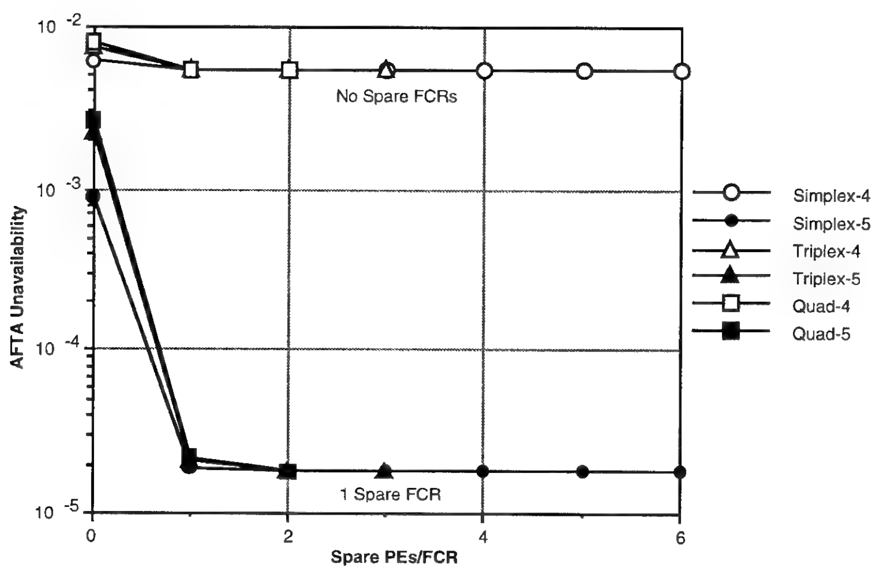

Figure 6. AFTA Unavailability vs. Number of Spare PEs and FCRs

VG Redundancy Level	Fleet Life Cycle Cost, $M
Simplex	4,030
Triplex	711
Quadruplex	724

Table 8. Fleet Life Cycle Cost vs. VG Redundancy Level

# PEs	4 FCR Power (W)	5 FCR Power (W)	4 FCR Wt. (lb.)	5 FCR Wt. (lb.)	4 FCR Vol. (cu. ft.)	5 FCR Vol. (cu. ft.)
5	145	163	43	53	0.51	0.62
10	220	238	48	58	0.60	0.71
15	295	313	53	63	0.69	0.80
20	370	388	58	68	0.78	0.89
25	445	463	63	73	0.87	0.97
30	520	538	68	78	0.96	1.06
35	n/a	613	n/a	83	n/a	1.15
40	n/a	688	n/a	88	n/a	1.24

Table 9. AFTA Weight, Power, and Volume vs. Number of Processing Elements

9.0 Summary and Conclusions

An Army Fault Tolerant Architecture has been developed to meet real-time fault tolerant processing requirements of future Army applications. AFTA is the enabling technology that will allow the Army to configure existing processors and other hardware to provide high throughput and ultrahigh reliability necessary for TF/TA/NOE flight control and other advanced Army applications. A comprehensive conceptual study of AFTA has been completed that addresses a wide range of issues including requirements, architecture, hardware, software, testability, producibility, analytical models, validation and verification, common mode faults, VHDL, and a fault tolerant data bus. A Brassboard AFTA for demonstration and validation has been fabricated, and two operating systems and a flight-critical Army application have been ported to it. Detailed performance measurements have been made of fault tolerance and operating system overheads while AFTA was executing the flight application in the presence of faults.

10.0 Acknowledgments

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AN INTEGRATED SYSTEM FOR AIR TO GROUND OPERATIONS

by
Massimo Avalle

ALENIA AERONAUTICA
System Technology dept. T341
Corso Marche 41 - 10146 Turin, Italy

ABSTRACT

The following paper describes, at the conceptual level, a possible solution for a system able to meet the hard requirements for attack A/Cs operating at low level into a high threat density scenario.

The conceptual study related to this work takes place from a research program related to air to air engagements, as some concepts mainly related to pilot workload reduction can be tuned up air to ground missions. A research program to deepely analyze the more important functions related to the safe penetration concept coud be initiated from this work.

Some of the main concepts related to low level A/C operations are overview and possible enhancements related to the technology trend and to possible new functions derived from enhanced system integration are discussed as an introduction for the system description.

The main functions forming the system will be described and an overview about the possible involved technologies will be supplied.

LIST OF SYMBOLS

A/C	Aircraft
C_3	Command Control Communication
FEBA	Forward Edge Battle Area
FLIR	Forward Looking InfraRed
F/W	Firmware
GLU	Ground Loading Unit
HDD	Head Down Display
HMS	Helmet Mounted Sight
HUD	Head Up Display
H/W	Hardware
IR	Infra Red
LOS	Line Of Sight
Rad Alt	Radar Altimeter
RF	Radio Frequency
RWR	Radar Warning Receiver
SA	Situation Assessment
S/W	Software
TF/TA/ThA	Terrain Following/ Terrain Avoidance/ Threat Avoidance
TTA	Target and Threat Assessment
TV	Television
VLSI	Very Large Scale of Integration

1 INTRODUCTION

Recent war experiences clearly show how aircraft operations in a modern battlefield characterized by high threats density become more and more difficult; as a simple example, penetration in such a scenario can no more be conducted just flying around individual threats, but the entire scenario conditions have to be taken into account.

The introduction of guided weapons, requiring Pilot attention during their aiming (sometimes an head-down operation) and the execution of manoeuvres after the weapon release, adds operational load to the Pilot, already involved in the A/C conduction, in the management of the onboard sensors and in the assessment of both the detected and planned targets/threats.

From the above considerations and taking into account the improvements in computer technology, bus communication, system design and weapon integration achieved in last few years, operational capabilities and effectiveness of attack A/Cs can be increased.

In particular the introduction of automation in some critical functions up to now devolved to the Pilot responsibility and the introduction of new functions, able to increase the A/C survivability in severe operative conditions becomes possible.

2 OPERATIONAL REQUIREMENTS

In addition to "usual" requirements for attack A/Cs, some more operational requirements for a system able to successfully support the operations of an A/C flying at low level in "all weather" condition and in a dense threat environment should be introduced; in particular such a system should be able to reduce the pilot workload and improve the A/C survivability during the penetration phase of the mission.

2.1 PILOT WORKLOAD

During the flight and especially during the engagements, the pilot is required to perform demanding tasks requiring a lot of attention and, as the tasks number and complexity increase, the

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related risk is the loss of attention for sudden, vital tasks. As an example, the following tasks could require simultaneous attention by the pilot.

- Maintain awareness of the total battle scene.
- Control multiple weapon release.
- Organize self defence against ground and airborne threats.
- Manage all the onboard sensors.
- Respond to onboard emergencies and failures.

Such problems can be countered by introducing automation in the system, relieving the pilot from repetitive tasks.

In addition to the above tasks, mainly related to the system conduction, some other pilot's demanding tasks involving the conduction of an Attack A/C in the scenario described in Section 1 can be singled out.

- It is difficult to fly the A/C at low altitudes and at night.
- When engaged by sudden, unplanned threats it is difficult to perform evasive manoeuvres avoiding to fly into the ground and without loose the ground protection.
- It is difficult to attack an opportunity target and safely return en route after the attack.

The above problems can be countered by introducing computer assistance features for the pilot into the system. The computer assistance for the pilot can be mainly subdivided in two types: system automation and tactical aids.

System automation represents essentially the transfer of some standard or repetitive tasks from the pilot responsibility to the system: examples can be sensors and resource management, flight control and pilot interface.

Tactical aids are "intellectual" tasks able to help the pilot to assess the tactical situation and the relative importance of targets and threats supplying the pilot with simple tactical indications during the combat phase or to plan a safe penetration path in the hostile territory.

2.2 A/C SURVIVABLE PENETRATION

The A/C survivability during the penetration in high threat scenarios can be improved by the introduction of some new functions in the system able to support precise navigation, avoid or at least reduce electromagnetic emissions, find the lowest risk path between the FEBA and the planned target and support the pilot in flying the A/C along such path.

2.3 REQUIREMENTS

Some main requirements for the system can be extracted from the necessity to reduce the pilot workload and support the A/C penetration described in Subsections 2.1 and 2.2. In particular the system should be able to perform the following tasks.

- Support the pilot during the target approach and, consequently, reduce his workload.
- Simple and exhaustive display of targets and threats in a format showing also the ground natural obstacles.
- In flight mission replanning.
- Quickly plan attacks against opportunity targets.
- Quick automatic reaction to counter unexpected threats.
- Support the penetration in hostile territory.
- "Silent" approach to the target.

3 REQUIREMENTS IMPLEMENTATION

The implementation of the requirements described in Section 2 leads to the necessity to develop some advanced and complex functions able to support Attack A/C operations in critical operational conditions.

An H/W architecture able to meet both the short computing time and fast data communication rate required by such functions is also necessary.

The implementation of such functions, together with the necessity to have an as wide as possible data source (multi-sensor suite) and the necessity to carry multi - purpose and intelligent weapons leads to the necessity to develop an highly integrated system able to take the maximum advantage from the available features, avoiding duplications.

System integration should involve also sensors and weapons (mainly, the "intelligent" weapons) in order to enable the implementations of advanced features related to weapon integration.

The requirements of the survivable penetration leads to the development of integrated functions mostly related to the capability of flying the A/C at low level following complex paths and to the necessity to reduce at a minimum RF emissions in order to avoid the alerting of hostile defences.

The navigation and attack capabilities guarantied by modern sensors and weapons have then to be fully exploited.

Beside other capabilities, such system should in particular be able to automatically fly the A/C on a planned path up to the designed target, replan the flight path at the detection of unplanned threats, manage the attack against opportunity targets, manage the onboard self defence facilities to counter planned threats or quickly counter immediate unplanned threats. In particular, active Radar emissions should be limited at the final target approach in order to guarantee an as silent as possible target approach.

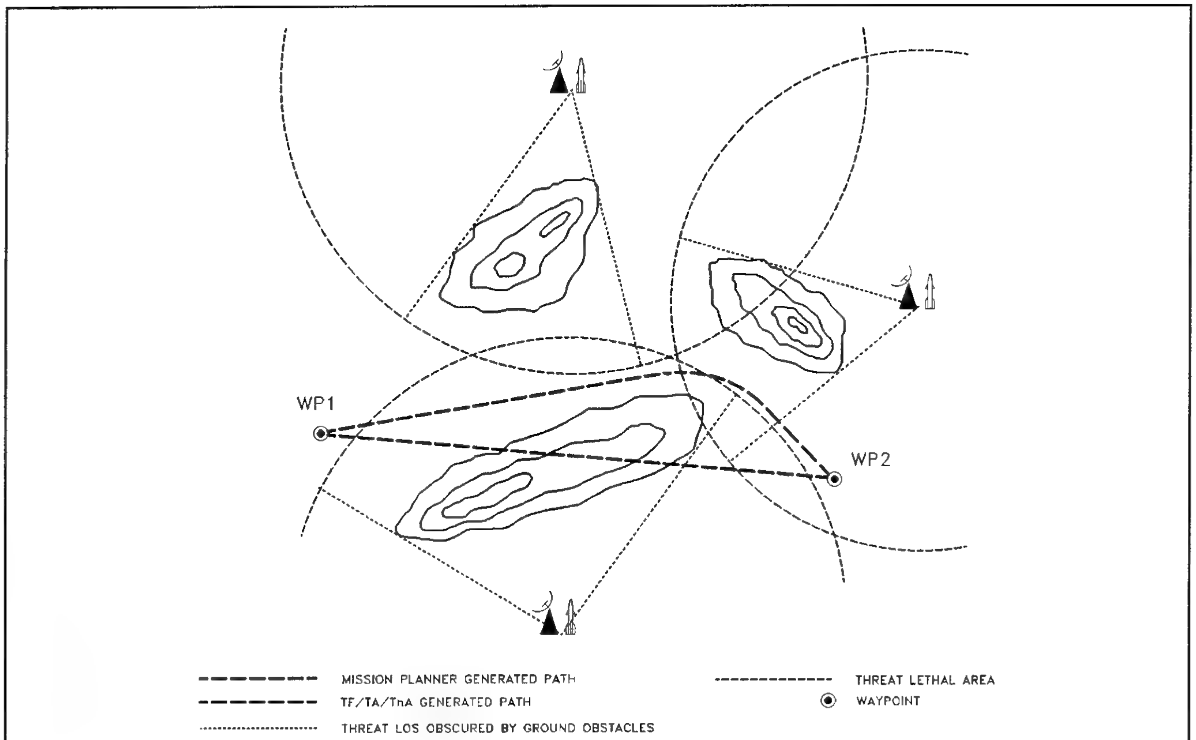

Fig. 1 - Survivable Penetration

In order to perform the above features, the system needs of an as correct as possible knowledge of the surrounding world obtained using an as wide as possible data source. In particular a multi-spectral sensor suite composed by Radar, IR and/or TV sensors and RWR should be used in conjunction with a Datalink connecting other friend forces and/or a C^3 System.

The Navigation System, beside its usual features, should be able to support the target silent approach by reducing at a minimum the active emissions.

Databases containing informations about Target/Threats and the development of databases with the terrain data of the operative zones are also necessary.

The integration of intelligent weapons can greatly improve the system effectiveness utilizing the sensors and the data storage capability of such weapons.

Another main requirement for such an integrated system is a fully integrated advanced cockpit, able to clearly supply the Pilot with the system outputs and to support simple and fast Pilot's interface with the system.

Advanced functions enabling the system operations and the technologies related to such functions are synthetically described in next Subsections.

3.1 ADVANCED FUNCTIONS

The implementation of some of the requirements described in Section 2 requires the utilization of advanced integrated functions able to support low level A/C operations. Implementation of such functions requires extensive use of integration systemwide to be implemented and involves S/W and H/W technologies related to Database management.

Following are briefly described some functions essential to support low level A/C operations and improve the mission success probability. More informations and some solutions for these functions can be found in References.

TERRAIN REFERENCED NAVIGATION

The TRN is an automatic and accurate navigation system able to relieve the pilot from the navigation task and allowing the active emission reduction, as the only active sensor is a low power Radar Altimeter. The integration of TRN with both the INS and the large digital terrain database allows the execution of frequent and not independent fixing. A Kalman filter is used to maintain accuracy between fixes or to maintain accurate navigation when fixing can not be performed. A steering facility allowing waypoint navigation or accurate A/C direction toward the target is also implemented into TRN.

PASSIVE TERRAIN FOLLOWING

The introduction of accurate databases containing terrain data in conjunction with an accurate knowledge of the A/C position enables the computation of a safe flight path over a minimum clearance height; such flight path can be coupled with an autopilot to obtain an automatic and passive TF. The necessity to operate the high power active TF Radar is then sensibly reduced, incrementing thus the A/C stealthness. The integration of such a system with the digital terrain database allows the system to know the ground profile behind the hills and laterally respect to the flight path, allowing the flight path prediction and the generation of three dimensional paths. The integration of terrain data with mission data allows also the individuation of safe, or at least minimum risk paths around threats.

PASSIVE PSEUDO-RADAR

Digital maps stored into memory and containing terrain data can be used to compute a passive pseudo-radar image to be displayed on HUD/HDD. This function is performed computing the LOS from A/C to ground, determining which points are visible from A/C and building a synthetic image of the terrain ahead. Utilization of such function allows silent target approach avoiding Radar emissions, as the tracking Radar sensor can be switched on just during the final target approach. The synthetic terrain image obtained from the passive pseudo-radar function can also be used to overlay either the real world or a FLIR image on HUD in order to prevent temporary loss of external vision by the pilot due to clouds or poor visibility conditions.

TF/TA/ThA

The TF/TA/ThA utilizes the digital terrain and mission databases to enhance the A/C survivability and penetration capabilities by the construction of a three dimensional flight path through hostile forces and threats from FEBA toward the target. Such three dimensional path is chosen with the constraint to avoid or at least to limit direct LOS to threats using ground obstacles to mask the A/C. Accurate navigation and silent low level flight are mandatory requirements, then the three advanced functions previously described have to be used and integrated together in order to develop an effective TF/TA/ThA function.

3.2 ENABLING TECHNOLOGIES

The advanced functions described in Subsection 3.1 are very demanding and require the adoption of relatively new technologies to be successfully implemented into the A/C Avionic System. Such technologies are mainly related to fast and accurate data management with particular attention to Database applications and involve the following areas:

DIGITAL MASS MEMORY

Database applications in aeronautics require a large amount of memory with fast access and re-programming time and at low cost. Standard media able to meet these requirements are magnetic tapes, laser disks and solid-state memories.

Magnetic tapes have their main advantage in the large storage at low price, while their main disadvantage is represented by limited environmental performances; in addition, frequent maintenance procedures are required and the tape transport speed limits the access time.

Laser disks have their main advantage in the large storage at low price (comparable with magnetic tapes), but altitude and temperature limits in conjunction with vibrational problems drastically limit their utilization. In addition, complex mechanical systems are required for their management.

Solid state memories (EPROM and EEPROM) have very fast access time and the production trend in last few years shows an increment in storage capacity in parallel with the cost reduction. The major limitation of EPROMs is represented by their erasure and re-programming time. EEPROMS do not have such limitation but their price is sensibly higher.

H/W DATA PROCESSING

In computer science, the migration of tasks from S/W to H/W (eventually with an intermediate step into F/W) is usual. In last years, the advent of VLSI digital circuits in conjunction with the last generation of high speed computers enables the migration of complex data management function into H/W, then the management of large amount of data in real time becomes possible.

DATA COMPRESSION TECHNIQUES

In database applications, data compression is mandatory in order to reduce size and cost of the required mass memory, as the compression process creates a true representation of original data without affecting the image quality. More reduction of the data amount can be obtained omitting some map data not used in particular applications. As digital maps are used also for the TF/TA/ThA function, real time decompression algorithms have to be implemented.

ADVANCED DISPLAY TECHNIQUES

An effective and "creative" display of digital maps is necessary to improve their readability and allow an utilization of registered terrain data beyond their simple visualization. Multifunction colour display can easily enhance by itself the digital map readability and understandability. Mission data and any other data can be pre-flight registered and overlaid to the digital map; the capability to modify such data in real time, by manual updating or via datalink from other friend forces can represent a relevant operational enhancement.

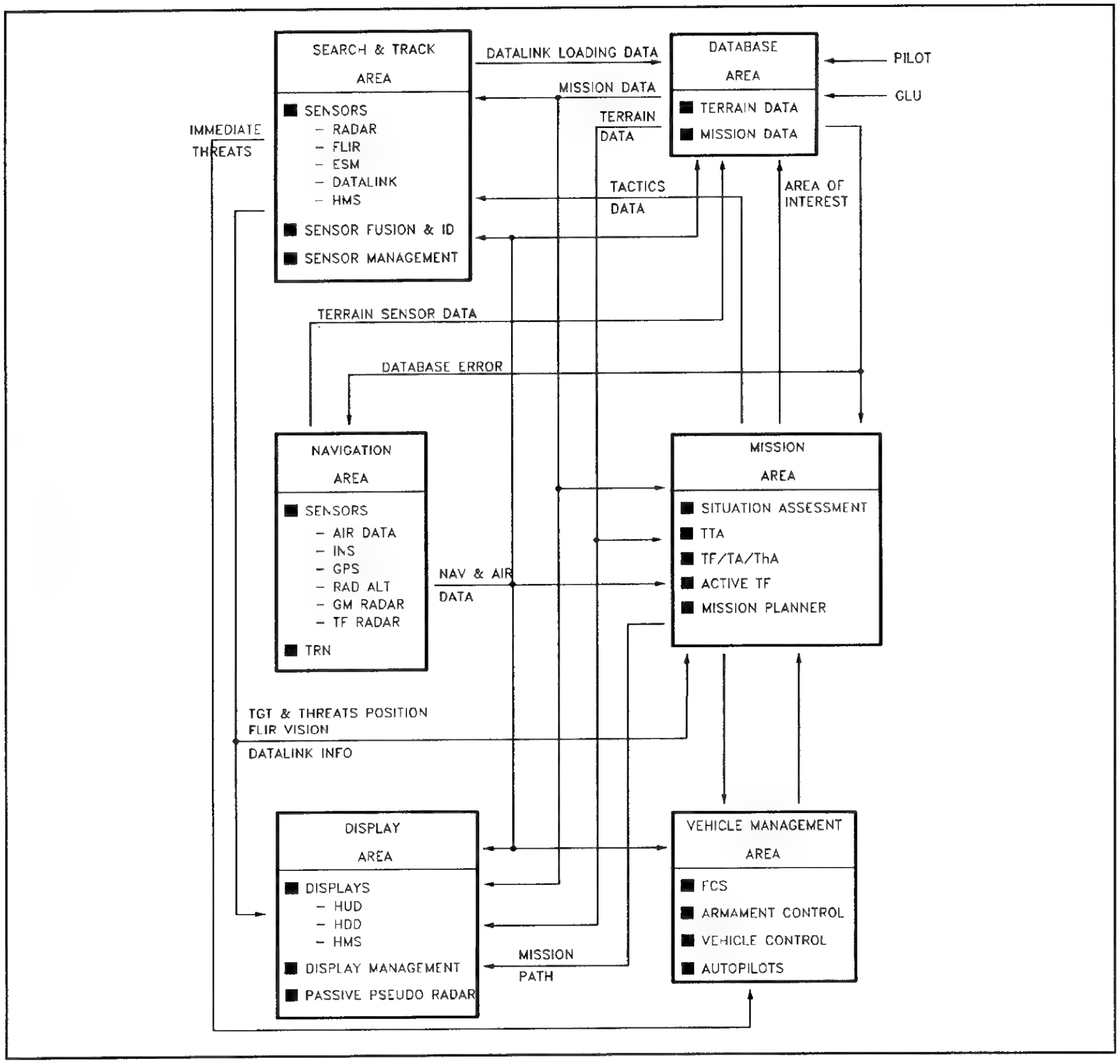

Fig. 2 - Proposed System Block Diagram

The capability to display passive pseudo-radar images in an effective format allows silent operations eliminating the need for Radar emissions up to the final target approach.

4 SYSTEM DESCRIPTION

The advanced functions described in Subsection 3.1, can be integrated together and with other A/C functions to build an integrated A/C system able to meet the requirements of Section 2.

In Fig. 2 is showed a conceptual system subdivision in main functional areas with their logical connections; the subdivision in functional areas has the purpose to facilitate the functions partitioning taking into account mainly their affinity, enabling in this way their integration by the functional point of view. The H/W architecture and, consequently, the system integration by the physical point of view, have to take into account such a functional partitioning.

Main functionalities and System operations are following summarized while particular areas operations will be described more exhaustively in following Sections.

By the conceptual point of view, full system operations start before the A/C flyes across the FEBA, with threats and targets acquisition via the on board sensors and datalink and with the assessment of the scenario situation performed by the SA and TTA functions. Future position of mobile threats is statistically estimated and updated upon the reception of their new position.

The Mission Planning function utilizes the data concerning fixed and mobile threats to compute a path to the target choosing a number of waypoints.

Significant changes in the position of the mobile threats or new threat detection can lead to the necessity to replan some waypoints.

The A/C flight path between two consecutive waypoints (see Fig. 1) is planned by the TF/TA/ThA function taking into account threat LOS obscuration due to ground obstacles (mainly, hills or valleys) together with estimated fuel consumption and time; as a main operational constraint, large deviations from the main path are not allowed.

Once the flight path is generated, the TF/TA/ThA function continues to evaluate possible path deviations along the way in order to be ready to react at unplanned threats detection or to readily react with evasive manoeuvres at immediate threat detection by ESM.

During the penetration phase, accurate, continuous and silent navigation have to be conduced in order to support the autopilots to follow the path computed by the TF/TA/ThA function with a sufficent accuracy. Accuracy and continuity are ensured by the integration of the terrain database data elaborated by TRN with the A/C position computed by the integrated INS/GPS.

The only active sensor utilized during this phase is a low power Rad Alt, ensuring in this way also the active emission reduction.

As stated before, the system performs a continuous, automatic and recursive scenario assessment in order to detect relevant changes in the targets and threats situation. If significant changes occurs, The mission Planning function evaluates the possibility to change some of the successive waypoints (not the one toward which the A/C is flying).

Once successive waypoints are changed by the Mission Planning, the TF/TA/ThA reacts accordingly, recomputing the corresponding safe path.

During the flight, the Passive Pseudo-Radar function generates a synthetic image of the ground that is overlapped on HUD to the "real" vision or to the FLIR vision in order to smooth lacks of ground vision due to clouds or bad weather. At the same time, the passive pseudo radar function computes also ground areas having a direct LOS with the A/C or just with the tracking Radar, enabling such sensor to be switched on just when target detection becomes certain and fast, as the search can be performed just into a limited area. On the other hand, areas having direct LOS to the A/C are overlapped, on a HDD display, to the ground map displayed to the pilot.

The above described system operations, coupled with proper autopilots, enable the A/C to fly along the safe path computed by the TF/TA/ThA function utilizing the Terrain Database data in conjunction with the A/C position, reducing the necessity of high power active emissions from the Terrain Following Radar.

Particular care is taken in the utilization of the terrain data as the possibility of errors or the presence of unknown or recently built obstacles like towers could be disastrous for the A/C safety. Then, data contained into the Terrain Database are compared with real terrain data obtained from the TF Radar, operated at very low power in order to collect terrain data along the A/C path at a relatively short range. Such data, together with the Rad Alt measurements and the navigation data are used to verify the congruence of the terrain data stored into the database.

If incongruence between Database, Rad Alt and Navigation data occurs, the Terrain Following Radar starts to operate at full power and the flight will continue using the standard TF capabilities obtained from the Rad Alt and TF Radar integration. The possibility to continue the mission along the safe path is evaluated on a case by case basis depending on the particular error occurred.

4.1 DATABASE AREA

Databases represent fundamental elements for an integrated system able to meet the demanding requirements concerning survivable penetration and to build the advanced functions described in Section 3.1.

A functional area is then dedicated, in this proposed system, to contain that functions able to support database operations.

Data stored into the databases are distributed systemwide to utilisers having different requirements, then the databases have to contain a wide variety of informations in order to facilitate system operations.

In Fig. 3 a conceptual scheme for the Database Area and of its interfaces is showed.

The Terrain Database stores the ground data related to the scenario of interest for the mission and is loaded at ground using a GLU.

The Mission Database stores the mission related data (like targets, fixed threats, waypoints), is loaded at ground using a GLU and can be modified in flight during the mission, either by the pilot or using Datalink informations. New threats detected during the mission are stored into the Database for successive analysis at ground and future use.

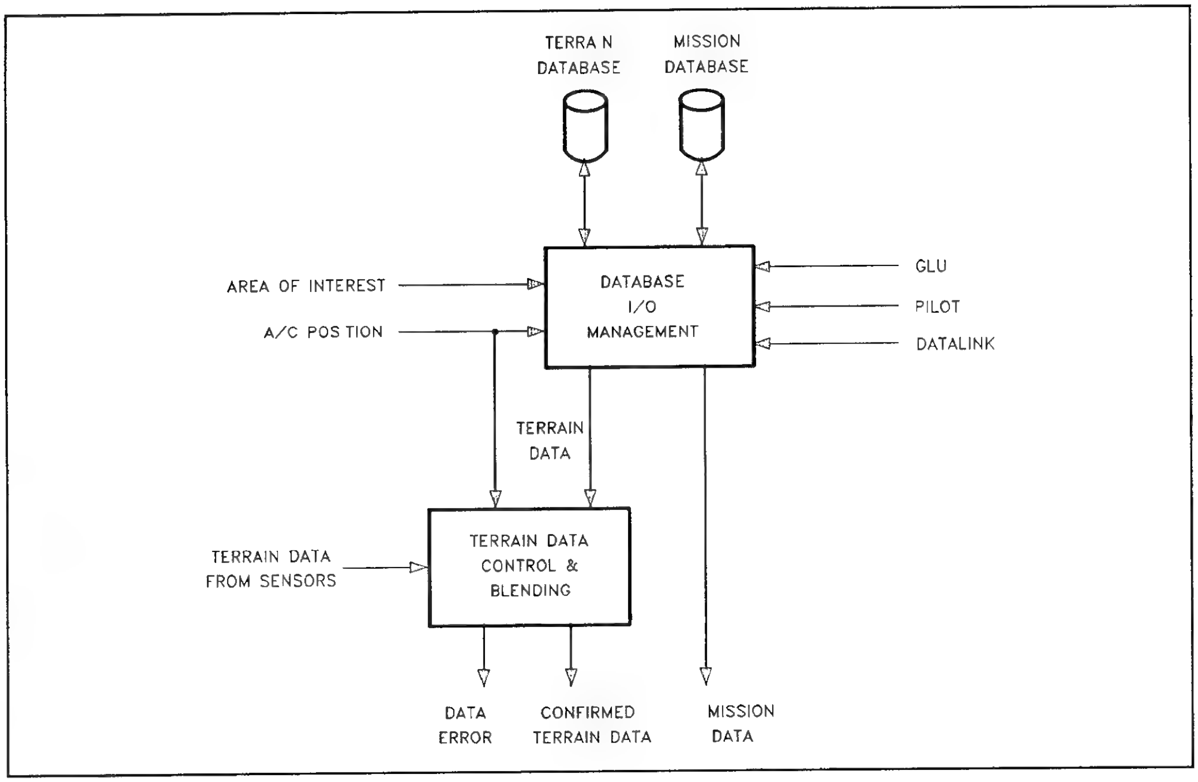

Fig. 3 - Database Area

During the flight, data concerning the ground area of interest selected by the Mission Area are red by the Database Manager function, de-compressed and organized in a useful format before to be distributed to the utilisers.

The control over the Terrain Database data congruence is performed by a specific function that compares the database stored data with the terrain data detected by the Terrain Following Radar. In case of Database data not congruent with the sensors data, both the Mission Area and the Navigation Area are alerted about the possible error. The Navigation Area reacts augmenting the range of the Terrain Following Radar, while the Mission Area replans the path to the next waypoint (if necessary) taking into account the new situation.

4.2 MISSION AREA

In the Mission Area are collected the tactical aid tasks like SA and TTA, the Mission Planning function and the TF/TA/ThA.

Fig. 4 shows a scheme of such area.

The SA function receives inputs from the Sensor Fusion and tries to deduce some further information, like for example the target class or objects groups, from the detected objects by interpreting the available data.

The TTA function processes the SA outputs in order to determine which are the more important targets and threats.

The Mission Planning function receives the additional target data computed by the SA and TTA functions and, combining such data with the best estimated A/C position selects the ground area of interest from the database. Ground data, together with position and lethality data about fixed and mobile threats are then analyzed and the waypoints to the target are selected.

The set of waypoints computed by the Mission Planning function are sent to the TF/TA/ThA function that utilizes database data and the selected ground clearance to compute the safe path between two consecutive waypoints.

During the flight along the safe path, the TF/TA/ThA function continuously computes possible escape manoeuvres in order to be ready to quickly react against immediate and unplanned threats; the expected path variation to enter again into the safe path is also computed with the constraint to maintain a low level flight over the ground clearance but without loosing, as far as possible, the ground protection and the threat obscuration ensured by the low level flight.

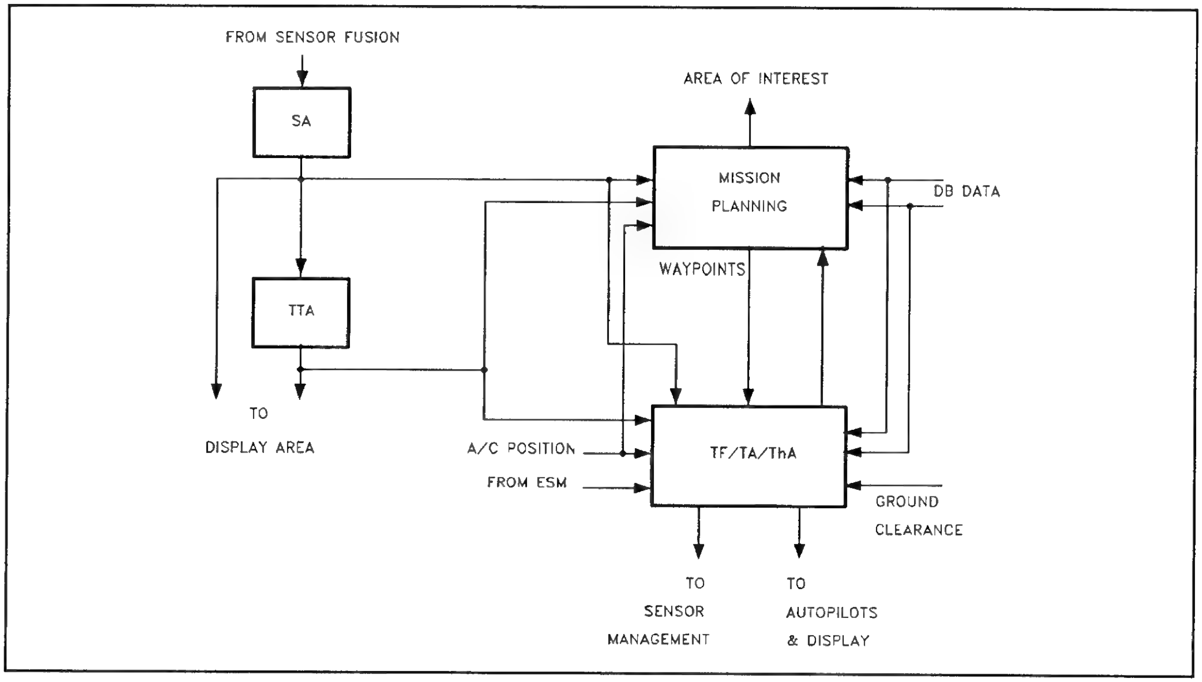

Fig. 4 - Mission Area

4.3 DISPLAY AREA

The Display Area contains all the display devices establishing the system visual interface with the pilot, the management functions and the display related advanced functions like the passive pseudo radar function.

The integration into the A/C avionics of large databases containing terrain and mission related data can greatly enhance the data display capabilities; as a consequence, some new features like map change of scale, zoom of an area of interest, scroll and rotation becomes possible.

The variety of informations contained into the databases can greatly improve the information display capability of the system by the development of advanced display techniques giving more flexibility to the displayed informations respect to the actual non modifiables maps.

A Display Management function is responsible for the management of the colours concerning the terrain elevation accordingly to the actual flight path and height, highlighting hazardous zones having higher altitude than the flight path.

Terrain and mission data together with the detection from the onboard sensors are overlaid in the Situation Display format showing the real position of threats and targets respect to the ground natural obstacles, enhancing the possibility for the pilot to plan attack paths approaching opportunity targets from the less dangerous sector.

The passive pseudo-radar function, together with the Synthetic Vision generation enhances the silent target approach capability and the night and/or bad weather vision enabling the displays to clearly show the "visible" ground areas on the Situation Display format and supplying the pilot with a synthetic ground vision overlapping the real vision or the FLIR vision on HUD; such syntetic vision can smooth the effects of sudden lack of visibility, reducing the pilot disorientation (see Section 3.1).

4.4 SEARCH AND TRACK AREA

In the Search and Track area are collected the sensors having the task to discover, identify and track targets and threats; the functions related to the fusion of the sensors data and to the automatic management of the sensors parameters are also provided in such area.

As showed in Fig. 2, the sensors form a standard multisensor suite covering a large band of frequencies, ensuring the all weather detection and the night vision capability.

The Sensor Fusion function processes the data relative to the objects detected by the sensors and received via datalink and compares them with the targets and threats data stored into the database in order to obtain an unique and as complete as possible object data set; further analysis about such objects will be performed in the Mission Area by the SA and TTA functions.

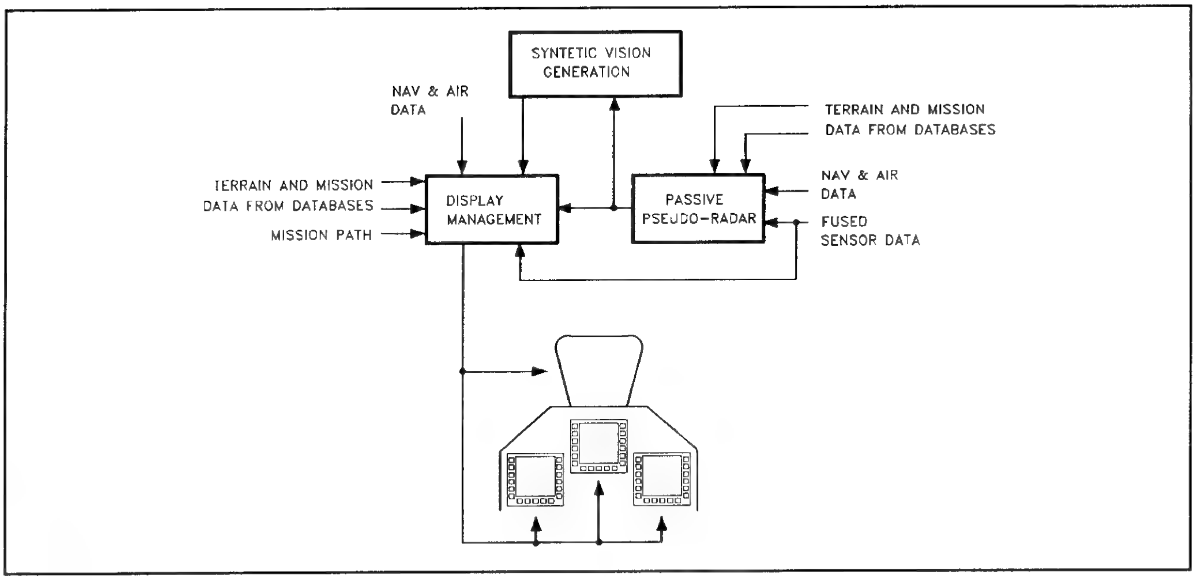

Fig. 5 - Display Area

The SM function relieves the pilot of many standard or repetitive sensor control functions and allows more complex and effective sensor controls like Radar automoding, scanner control and cross sensor cueing that are beyond the human capability.

4.5 NAVIGATION AREA

In the Navigation Area are gathered the sensors and the functions related to the acquisition and elaboration of the A/C position, of the air data and of the ground elevation data. A specific management function is responsible to collect the sensors informations and to compute the best estimated A/C position.

A wide and integrated sensor suite for the Navigation Area has been chosen in order to guarantee the high accuracy in the A/C position estimation that is necessary to achieve accurate database utilization and consequently to reduce the necessity to operate at full power the Terrain Following Radar.

In conjunction with accuracy, a workload reduction for the crew in the navigation task is also ensured by the TRN automatic capability to generate navigation fixes without operator intervention.

INS and GPS are integrated via a Kalman filter in order to merge the short term accuracy of INS with the long term accuracy of GPS; the INS is periodically recalibrated using the GPS measurements to eliminate the temporal error.

The output of the Kalman filter is sent to the TRN and used to compute the relative horizontal location of Radar Altimeter measurements and then achieve the position fixing.

4.6 VEHICLE MANAGEMENT AREA

In the Vehicle Management Area operates the functions related to the vehicle and armament management, the autopilots and the flight controls.

The autopilots receive as input the mission waypoints and the three dimensional safe path computed by the TF/TA/ThA function and are responsible to physically fly the A/C along such path, generating proper outputs for the FCS.

The armament control, beside the usual operations concerning weapon selection and priming, is also able to perform some more "creative" operations utilizing the integration of weapons with other avionic functions.

An example of particular weapon integration applicable to attack A/Cs and utilizing the features offered by the high level of integration of the system and by the onboard database is following described.

Terrain data stored into the on-board database can be used to download the avionic of a stand-off weapon prior to launch, obtaining the last minute retargetting capability and augmenting in this way the operational flexibility.

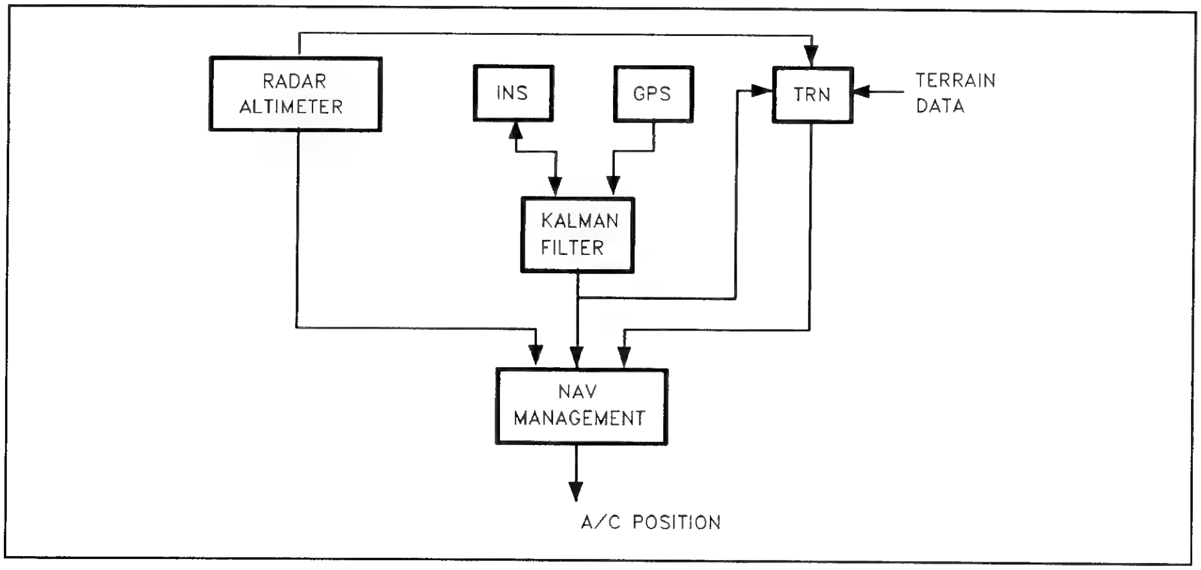

Fig. 6 - Navigation Area

5 CONCLUSIONS

A possible solution for a system able to enhance the survivability and the mission success for a ground attack A/C has been described in this paper.

The relevant role in the system effectiveness is played by some advanced functions (described in Section 3.1) that effectively ensure a performance upgrading respect to existing systems.

The development of such functions requires the integration of navigation, object detection and data storage functions and fast data exchange between functional areas.

A possible problem can arise from the pilots reluctance to fly an A/C whose safety is demanded to the correctness of a database, in the same way as there was reluctance to fly the active TF systems when they was introduced.

The problem develops from the poor confidence in the capabilities of new systems that have not yet demonstrated their effectiveness and capabilities. The solution to such a problem should be the demonstration that the system really works, using a flight simulator facility at a first stage and in successive stages of flight testing. During the initial flight tests, the system should operate in parallel to an active TF system, and post flight debriefing have to demonstrate its effectiveness, also in presence of simulated database errors.

Successively, the power of the active TF should be gradually reduced in order to demonstrate the system operational effectiveness and the stealthness enhancements.

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Laser Based Obstacle Warning Sensors for Helicopters

W. Büchtemann
Eltro GmbH/DASA
Kurpfalzring 106
69123 Heidelberg
Germany

M. Eibert
Dornier GmbH/DASA
88039 Friedrichshafen
Germany

1. SUMMARY

Helicopters and aircraft in low-level flight have a high risk to strike obstacles, in particular power lines and overhead wires down to the size of telephone wires. This risk increases when flying nap-of-the-earth (N.O.E.), at night and under poor visibility conditions. Existing night vision equipment cannot provide safe detection of these dangerous obstacles. For these reasons there has been, for quite some time, a widely accepted need for reliable means of detecting obstacles, particularly under all acceptable Low-Level and N.O.E. flying conditions.

Solutions to this problem, proposed and developed in the past, have been mainly based on millimetre wave technology. More recently, laser based system are being developed which offer good capabilities to solve this task without many of the shortcomings of the radar systems. The laser radar solution, on the other hand, has to prove its adequacy under limited visibility conditions.

This paper presents laser radar developments in the thermal infrared (10 μm region) and near infrared spectral regions for helicopter obstacle warning systems. Both Dornier and Eltro have designed, built and demonstrated laser radar sensors for obstacle warning. Eltro has designed and built an experimental laser radar based on CO_2-lasers and heterodyne detection. Ranges in excess of 600 m against railway overhead wires and 1100 m against extended targets have been achieved. Dornier has designed, built and flight demonstrated a GaAs laser obstacle warning sensor operating at 0.9 μm. Merits and limitations of these technologies are being discussed.

Based on the experience gained over several years and taking into account recent developments in the solid state laser area it was recognised that the NIR is the best trade-off in terms of performance, cost and weight, in particular for helicopter applications. Consequently, Dornier with Eltro as subcontractor develop currently an experimental laser radar operating at 1.5 μm. This laser radar will enable the pilot to detect wires at a distance of app. 400 m even under limited visibility conditions. Sensor concept and the architecture are being presented.

2. INTRODUCTION

Helicopters are still gaining importance in the military sector as the significance of fast reaction and high mobility increases, as well as the need for search and rescue flights. Also in the non-military sector, the search and rescue aspect as well as surveillance missions and short-distance VIP missions gain in importance.

For all helicopter operations and missions close to the ground there is a risk of a collision with obstacles. The most dangerous obstacles are wires of all types including telephone wires due to their low observability. Amongst the total range of this category of obstacles, high-voltage power lines cause the majority of accidents. The need for a wire detection system arises in particular for night operations because the existing night vision equipment, both image intensifier goggles as well as thermal imaging devices do not guarantee a reliable detection.

Therefore, the need for an obstacle warning system has been recognised for some time. Recent studies have shown, that laser radar technology is suitable for flying platforms without the disadvantages of mm-waves. Such an obstacle warning system (OWS) would then be called more specifically obstacle warning laser radar or obstacle warning ladar (OWL)

For civil operations a comparatively simple OWL would suffice to ensure safety in rescue missions, police operations and surveillance missions, because operation close to the ground is only required during takeoff and landing and the pilot is essentially free to select the speed according to the specific circumstances, e.g. visibility.

In military missions, much more stringent requirements exist in order to pursue as close as possible the original mission plan which includes maintaining high speed and minimum height above ground. This can only be achieved with the help of an obstacle avoidance system which has a minimum range of several 100 m even under limited visibility conditions and which is integrated in the avionics system.

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

3. REQUIREMENTS AND SYSTEM APPROACHES

For an experimental wire warning system funded by the German Procurement Office requirements were formulated. An all weather capability of the wire warning system is not required because the warning system is not intended to provide in itself an all weather capability. However, the range against wires should be 500 m when the visibility is 500 m or above. When the visibility is below 500 m the range should be at least equal to the visual range. For an obstacle detection range of 500 m a refresh rate of at least 2 Hz is required if one assumes a required reaction time of 8 s and a speed of 120 kn. Tab. 3.1 shows the system data which were requested for an experimental system by German officials based on the above and further considerations.

Wire detection requirements	
Detection range against wires of 5 mm at 45° incidence at visual range of 500 m	≥ 500 m
Field of view with fixed sensor	40° x 60°
Range of mechanical movement of FOV axis	50° x 120°
Depth resolution	15 m

Tab. 3.1: Requirements for a wire detection system.

Although systems using mm-waves offer an almost all weather capability (only heavy rain would incapacitate the system); they have the disadvantage that detection of wires under angles of 45° is not feasible with practical systems. The remaining spectral regions are to be found in the near infrared or in the 10 μm-range.

Fig. 3.1 shows an installation configuration of such an obstacle warning laser radar.

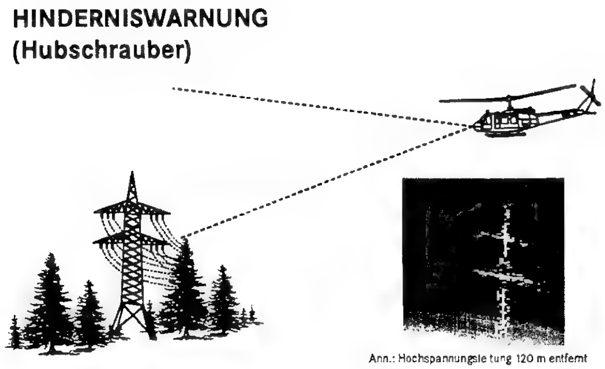

Fig. 3.1: Installation configuration of an obstacle warning laser radar.

Laser radar (or ladar) systems used for obstacle warning are imaging sensors. They will generate range images using time of flight measurements usually on the basis of pulses or modulated cw signals. To visualise such a range image, a particular range bin can be coded in colour or in grey values. Fig. 3.2 shows the example of a normal and a range image generated with laser pulses.

One big advantage of lasers is their small divergence which results in a high angular accuracy and high signals against wires or other objects with small dimensions. There is a problem with this small laser divergence: A contiguous coverage of the field of view in 2 dimensions is not possible. One uses a 1-dimensional contiguous scan, e.g. line scan, and a scan pattern which nonetheless ensures the certain detection of dangerous objects, see e.g. Para. 4.1.

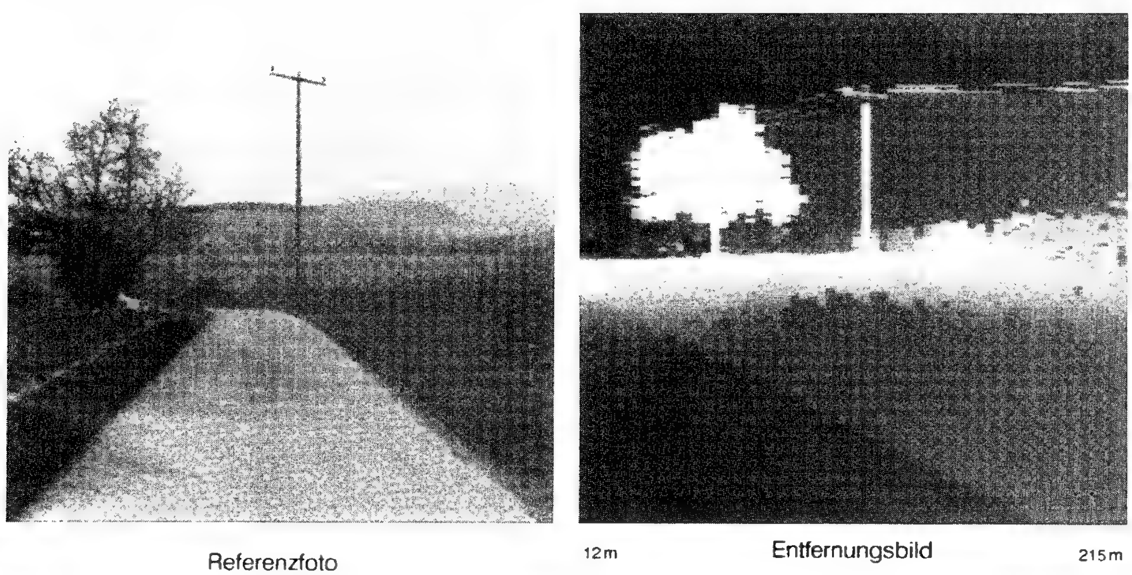

Fig. 3.2: Example of a range image (right) and the reference photograph (left). Ranges were coded originally as colour values and converted to grey values for the printing process.

The fact that the scan does not cover the object space contiguously has a major advantage: The detection of a laser beam outside its nominal beam radius is very difficult, in some cases virtually impossible. It is quite feasible that a laser detector inside the OWL field of view does not detect the laser transmitter unless directly struck by the laser for which only a low probability exists. Prerequisite are well designed exit optics: Stray light in the optics will deteriorate the covertness of the system.

4. CO_2-LASER RADAR WITH HETERODYNE DETECTION

CO_2-laser technology is of very high interest on the one hand because the CO_2-laser has a very high efficiency, the overall efficiency ("wall plug efficiency") can exceed 10%. Even including power supply and cooling, very compact systems can therefore be built.

Furthermore, in the CO_2-range (9-11 µm, nominally 10.6 µm) the atmospheric transmission usually is considerably better than in the visible, in particular when the visibility is low. This ensures a high availability, i.e. the nominal ranges are seldom reduced by atmospheric effects. Dense fog, however, negates the operation of a CO_2-system. One is compatible, however, with a thermal imaging pilot night sight which is also used under adverse weather conditions. The above mentioned and further advantages, see Tab. 4.1, led to early implementations of CO_2-laser radar systems. One of the firsts systems was LOWTAS, developed by UTRC. A more recent example is CLARA, a joint development of GEC Ferranti and Dassault. Partly funded by the German Procurement Office, Eltro has built and tested an experimental CO_2-obstacle warning system, see below.

CO_2-Heterodyne Laser Radar	
Advantages	**Problems**
Efficient, powerful laser transmitter. Wavelength tuneable in the 9-11 µm range	Comparatively small reflection coefficients, in particular against wet targets
High sensitivity by heterodyne detection	high system complexity, cooled detector required
Good atmospheric transmission: high ranges and high temporal availability, range compatibility with thermal imagers	Expensive EO-components
"Eyesafe" wavelength	
Measurement of relative speed by exploiting the Doppler effect	
High frame rate due to high laser repetition frequency	

Tab. 4.1: Advantages and problems of a CO_2-laser radar

Conclusions from experience with the Eltro system and the analysis of other sources can be summarised as follows: Regarding the performance in terms of range, frame rate and availability in connection with atmospheric effects, the CO_2-laser radar is difficult to surpass. The complexity of the heterodyne detection and the resulting weight and cost would suggest primarily the use with fixed wing aircraft. With the recent, rapid development of eyesafe ($\lambda \geq 1.4$ µm) laser sources in the NIR (solid state lasers, in part with frequency shifting) the CO_2-laser may encounter competition even in that field.

4.1 Eltro obstacle warning sensor HIWA

The experimental obstacle warning sensor HIWA, developed by Eltro, is a heterodyne-CO_2-laser radar with a following display processor. The functioning of the sensor head can be gathered from the block diagram in Fig. 4.1: An HF excited cw laser is Q-switched by a photo elastic modulator and emits a linearly polarised radiation ("pulse laser"). The radiation is guided through a Brewster plate and a reflective phase shifter which introduces a 90° phase shift in one polarisation direction thus causing a circular polarisation. This radiation is deflected by 2 wedge scanners, each consisting of two counter rotating wedges. The thus obtained scan footprint would be almost horizontal. For

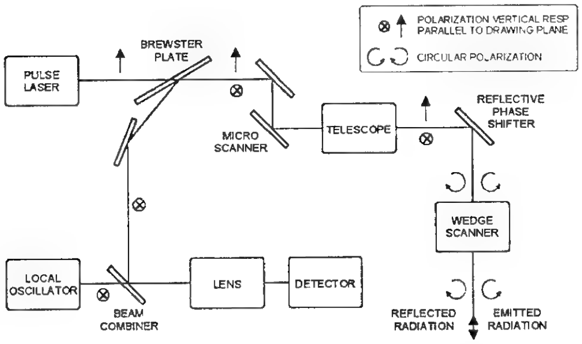

Fig. 4.1: Block diagram of the CO_2-heterodyne laser radar

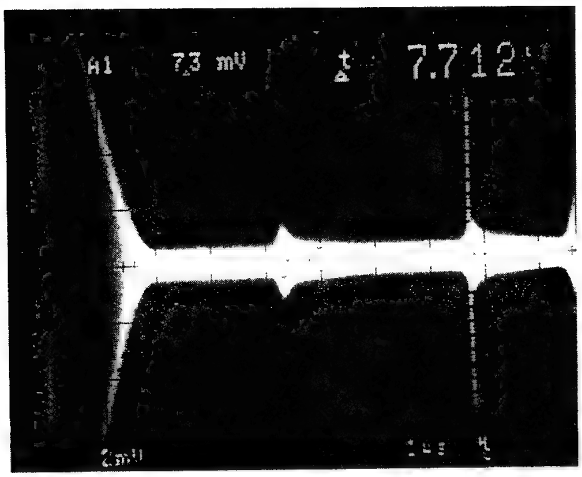

Fig. 4.2: Signals in the case of an overhead wire at 635 m and a tree at 1155 m

this reason a micro scanner has been introduced to generate a fast oscillation in the vertical direction which in turn guarantees the detection of horizontal wires.

A coaxial system was realised: the reflected signal enters the system via the wedge scanner and is subsequently converted to linear polarisation by the phase shifter and reflected by the Brewster window into the detection channel, where the local oscillator radiation is superimposed onto the signal radiation and finally detected by a cooled MCT detector.

Fig. 4.2 shows signals which were taken directly from the output of the preamplifier (intermediate frequency, IF). There is a double target: A railway overhead wire at 635 m and a poplar at 1155 m. The visual range was approx. 2 km.

HIWA was designed to provide a sensor head which allows to investigate fundamental, e.g. wavelength dependent effects, as a tool for system optimisation. The system HIWA, see Tab. 4.2, demonstrated that the theoretically expected performance, e.g. range and frame rate, can be achieved. The system was delivered to the customer and can now be used for further investigations.

ELTRO LASER RADAR HIWA	
Type of radar	Coaxial CO_2-laser radar using heterodyne detection
Scanned FOV: Azimuth Elevation	60° 30°
Scan pattern	Horizontal swathes with vertical micro scan and overlapping footprints Mean vertical distance: 1°
Ranges	> 800 m against 20 mm wires > 1000 m against topographical targets
Scanner	2 pairs of Germanium wedges of app. 105 mm diameter
Frame rate	up to 5 Hz

Tab. 4.2: Parameter of ELTRO laser radar HIWA

5. OBSTACLE WARNING SENSORS IN THE NEAR INFRARED

Compared to the 10 μm range the near infrared (NIR) has some physical advantages: Due to the smaller wavelength, objects with a smooth surface exhibit a more Lambertian reflection behaviour, i.e. the detection of wires seen under oblique angles is less critical than with a 10 μm system, which in turn is much less critical than with mm-waves. In all practical cases the atmospheric transmission is equal or superior to the transmission in the visible. Some attention has to be drawn to the compatibility with thermal imaging: A absolute guarantee cannot be given that sufficient laser radar range is available when a certain range with the thermal imager is present. A safe use of the NIR obstacle avoidance system is nonetheless guaranteed: The laser radar can obviously establish the range against topographical targets. Using this value, the atmospheric extinction and the range against wires can be inferred with the same confidence level as under clear weather conditions. Furthermore, long term transmission measurement programs, in particular the OPAQUE program, did show that for the considered ranges (approx. 500 m) cases of drastically diverging atmospheric aerosol extinction (in the NIR vs. 10 μm), are comparatively rare.

Two spectral regions within the NIR are of interest for obstacle warning systems. This is on the one hand the range up to 1 μm. Eye safety considerations limit the maximum laser output power or energy. For this reason, such systems are the domain of semiconductor lasers due to their technical maturity and moderate price.

If higher performance is required in terms of range and frame rate, one is forced, for eye safety reason, to go beyond 1.4 μm. In this case, the atmospheric transmission mandates the range beyond 1.5 μm, on account of the detector technology the long wave limit is just 1.6 μm. In this spectral niche very good detectors are available as a spin off product of the fibre optic cable transmission systems. Lack of suitable laser sources prohibited in the past system considerations in this spectral range. Just now suitable lasers are emerging, in particular frequency shifted Nd-lasers and Er-lasers.

5.1 Obstacle Warning Sensors at 0.9 μm

If wire and obstacle detection ranges, field of view and the image refresh rate are kept within moderate operational limits, the 0.9 μm solution results in a cost-effective, light-weight warning system.

For operations such as rescue flights (operation close to ground is only required for takeoff and landing) a 0.9 μm system will considerably improve flight safety. Taking into account eye safety limits, the following maximum obstacle detection ranges can presently be achieved with this class of warning systems:

- 600 m extended area obstacles
- 400 m single lines with a diameter of 25 mm
- 300 m single lines with a diameter of 10 mm.

These obstacle detection ranges and operational conditions are sufficient for most civil operations. An obstacle warning sensor would thus considerably increase flight safety of non-military helicopters.

When determining the OWL (Obstacle Warning Laser Radar) parameters operational requirements are to be considered. For example, the image refresh rate is derived from the maximum flight speed. At a flight speed of 20 m per second and an image refresh rate of 2 Hz the obstacle scene in the field would be refreshed every ten meters of travel.

The OWL scanning geometry is based on the Dornier-developed ladar scanning configuration. The fast horizontal scanning is performed electronically (multiplex method with diode array) and the vertical scan is performed mechanically (with a fibre-optics scanner). This technique was demonstrated in experimental units and series products. Considering the mature and comparatively inexpensive technology of transmitter and detector arrays operating at 0.9 μm, a pulsed, imaging ladar with electronic horizontal scan (line) and mechanical vertical scan (column) is considered to be a highly efficient solution for OWL.

In order to detect small objects contiguous scanning is carried out in vertical direction with the oscillating mirror. This results in a scanning ratio of 5 to 1 or 320 to 64 pixels for the selected OWL parameters.

Test results with Demonstration OWL

To support this 0.9 μm concept, a functional demonstrator had been implemented with reduced parameters. The fundamental wire detection could in the first step be demonstrated in ground tests followed by flight trials. In both test series image data were recorded as digital range images. The data were displayed in real time on a monitor by coding range data both in grey and in colour values. To reproduce the results gained in the ground tests, obstacle detection was carried out in hover and low level flight. For these trials, the OWL was hard mounted to the left helicopter pylon in a position where no vignetting occurred, see Fig. 5.1 and 5.2.

The analysis of these test data resulted in the following obstacle detection ranges

Fig. 5.1: Helicopter CH 53 equipped with demonstration OWL

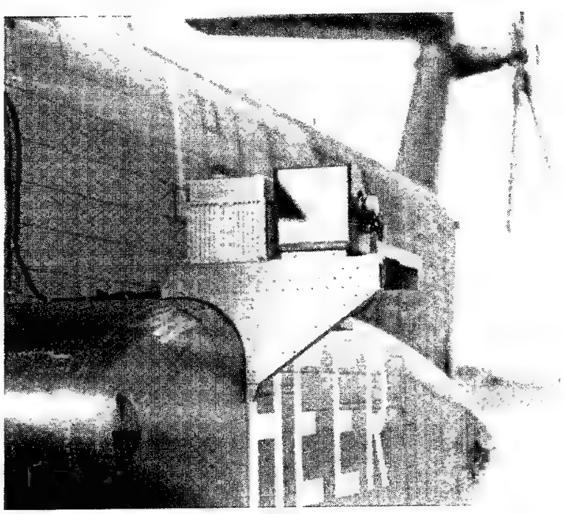

Fig. 5.2: Installation of the demonstration OWL onto the pylon of the CH 53.

Fig. 5.3: Example of the system's performance against wires

- Wires 80 m to 130 m
- Poles (masts) 150 m to 220 m
- Extended objects 300 m to 400 m.

5.2 1.5 μm Obstacle Warning Sensor

Signals obtained from wires exhibit an r^{-3} dependence, this means that, other parameters being equal and atmospheric effects not being taken into consideration, the laser power has to be multiplied by 8 if the range is to be doubled. In addition, the atmosphere has an essential impact on detection ranges.

It appears that to obtain the ranges indicated in Para. 3, one needs pulsed laser powers in the kW range compared to laser powers in the W region permitted on account of eye safety consideration at 0.9 μm. Fortunately, the kW pulse power is still eye safe at 1.54 μm when the pulse length is about 10 ns leading to a pulse energy of approx. 100 μJ.

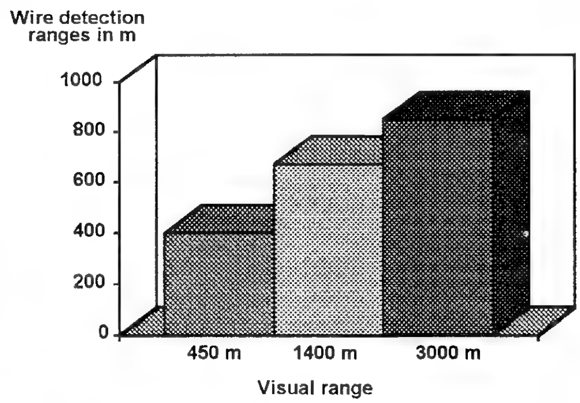

Fig. 5.4: Ranges of a hypothetical system against 5 mm wires with 10 kW pulse power for visual ranges of 450 m, 1400 m and 3000 m.

Due to recent developments in the field of diode pumped lasers (Nd and Er) as well as in the field of crystals used for frequency shifting, laser sources are now available at 1.54 μm exhibiting pulse energies in excess of 100 μJ at repetition rates of several tenths of kHz. With such a system the detection of thin wires according to the requirements stated in Para. 3 is possible.

In a study for the Federal Office of Defence Technology and Procurement (BWB) Dornier with Eltro as subcontractor develop an OWL/OWS (Obstacle Warning System) for helicopters with parameters summarised in Tab. 5.1.

The most critical item is the laser source. To minimise the risk, two different solutions are being pursued.

Sensor type	Scanning laser radar
Laser transmitter	Solid-state at 1.54 μm
Scanning	2 axis: vertical oscillating mirror horizontal fibre optics
Image repetition frequency	≥ 2 Hz
FOV	32^{o} x 32^{o}
Ranges	≥ 500 m (wire ≥ 10 mm, good visibility) > 300 m (wire > 10 mm, adverse weather, oblique incidence,) ≥ 600 m (extended objects, good visibility) > 400 m (extended objects, adverse weather)
Angular resolution	< 0.5^{o} horizontal ≤ 0.1^{o} vertical
Range resolution	≤ 1m
Pixels	64 horizontal 320 vertical

Tab. 5.1: Performance summary of the 1.54 μm laser radar

A Dornier-developed fibre-optic scanner, see Fig. 5.5, which already has been employed as a series product, provides the fast line scanning which is necessary for this OWL. For image generation, column scanning is carried out with an oscillating mirror. This ladar concept as a whole as well as major parts of it have been already tested with the electronic line scan in the 0.9 μm OWL described in Para. 4. Test results were very positive and showed that this laser radar concept is optimally suited for the detection and location of wire shaped objects

The data summarised in Tab. 5.1 are conservatively calculated for the first demonstration model. It is expected that by optimising the system without changing the overall layout, the ranges can considerably be improved, i.e. ranges of more than 800 m against wires under clear weather conditions can be expected. In addition, the image repetition frequency can be increased.

A special characteristics of this OWL is its simple structure which bears a potential for small and light weight system components. An

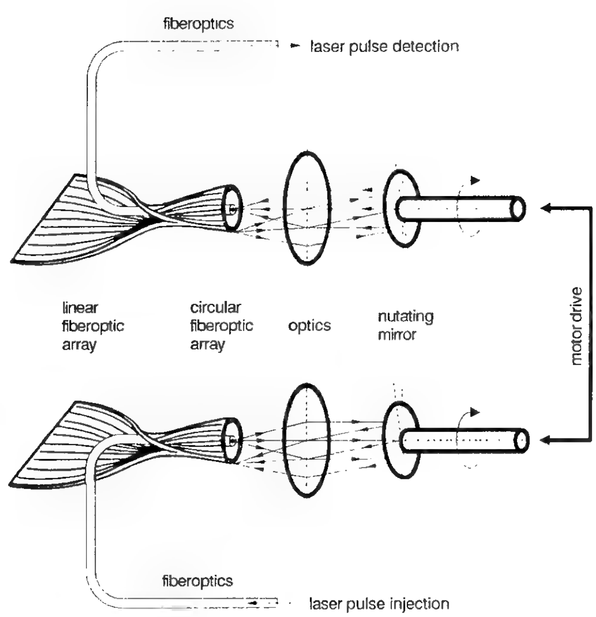

Fig. 5.5: Fibre optics scanner

example is the fibre-optic scanner with a length of 17.5 cm, a diameter of 30 mm and a weight of only 250 g. Scanner control in the 1.5 μm OWL is carried out by means of a single Euro-card.

Due to previous work and the use of proven components it will be possible to start ground tests with the 1.5 μm system in autumn 1994, followed by the first flight test by the end of this year. The flight tests will be extended and continued in spring 1995 and expanded to the system level (OWS) by a real time processor for obstacle detection. This system development phase will be continued until the end of the study in mid 1996. Processing methods will be selected during development in order to define the OWS configuration. At the same time, the optimisation and testing of the OWL functions will continue.

6. RESULTS AND OUTLOOK

Obstacle warning systems on laser basis enable a reliable detection and location of dangerous obstacles such as lines, wires, cables, antennas, towers etc. which may pose a safety risk in low-level helicopter missions. Additionally, the multitude of laser sources permit tailored obstacle warning systems for different mission requirements. "Lean" OWLs operating at 0.9 μm can be built with semiconductor lasers, photo diodes, simple detection circuits for civilian and simple military missions. Such systems have been extensively tested in ground and flight tests.

In order to achieve sufficient range even under limited visibility conditions for military low-level missions, eye safety consideration mandate a wavelength beyond 1.4 μm. To avoid the complexity of 10 μm-systems, the sum of considerations regarding atmosphere, target characteristics, technology and covertness lead to a 1.54 μm system. Such a system is being developed. The performance of the sensor front-end is fairly well defined, because mainly proven components are being used. For the most critical item, the laser source, two technical solutions are being pursued allowing to minimise the risk. A major task for the success and acceptance of the system is to provide tailored processing and integration into the aircraft as well as the data display to the pilot.

Development and Flight Testing of an Obstacle Avoidance System for U.S. Army Helicopters

Sandra L. Holder
Robert G. Branigan
U.S. Army
Night Vision and Electronic Sensors Directorate
10221 Burbeck Road
Fort Belvoir, VA 22060-5806, U.S.A.

1.0 SUMMARY

Today's Army Aviator must fly both low and fast in order to survive against modern anti-aircraft weapons. Such flight brings him perilously close to wires, poles, trees and other obstacles. Helicopter collisions with such obstacles have been a long-standing concern for the United States Army.

In order to address this issue, the Night Vision and Electronic Sensors Directorate (NVESD) has sponsored the development of an Obstacle Avoidance System (OASYS) capable of being integrated onto an aircraft and operated in real time. Under this program, two different systems have been fabricated and delivered. Both systems utilize direct detection laser radar sensors which operate in the eyesafe regime. The two systems differ primarily in the type of laser source used. The first system, developed by Northrop Corporation, utilizes a diode laser operating at 850 nm with an average repetition rate of 64 kHz. The second system, developed by Fibertek Inc., utilizes a diode-pumped solid-state laser operating at 1.54 microns with a repetition rate of 15 kHz.

Both systems have been integrated onto helicopters and extensive flight evaluations have been completed. A number of important lessons have been learned regarding the individual technologies involved and obstacle avoidance as a whole. Both systems have been demonstrated to enhance mission effectiveness and flight safety. Furthermore, the technologies have been shown to be mature enough to justify proceeding to an Engineering and Manufacturing Development (EMD) phase in which issues relating to cost, volume and weight are addressed.

2.0 USER REQUIREMENTS

The need for an Obstacle Avoidance System for Army helicopters has been well established. In 1988, a requirements document was drafted by the user community to address this need. The requirements as contained in this document are summarized in Figure 1. Most of them are self explanatory, but a few words need to be said about the first two.

2.1 Aircraft Protection

The specification for 90% aircraft protection was an acknowledgment of the trade-off between system performance versus size and weight of the sensor. To guarantee 100% protection would require a sensor which could not meet the size and weight requirements which are so critical for helicopters. It was believed, however, that 90% protection could be achieved with a system which met the weight specification. In addition, the requirement was only applied to coordinated terrain flight in order to avoid the need for 360 degree coverage. Protection of the aircraft while hovering or moving sideways or backwards can be achieved by a less sophisticated sensor since flight in those directions is less precise and aggressive.

USER REQUIREMENTS

- 90% aircraft protection in coordinated flight
- Day/night/degraded atmosphere operation
- Visual cueing of obstacles
    - use existing or planned displays
    - no dedicated operator
- System must be eyesafe
- Production cost not to exceed $150K
- Production weight not to exceed 40 lbs

Figure 1. Requirements for Obstacle Avoidance.

2.2 Daytime vs. Nighttime Operation

FLIRs and Night Vision Goggles have gone a long way towards turning night into day, however they still do not provide the pilot with the same visual acuity that he has during the daytime. OASYS was intended to further bridge this gap, thereby allowing the same aggressive flight behavior at night as is possible during the day.

Daytime obstacle detection requires a more robust sensor because of the intense solar noise background. Applying the requirement of 90% aircraft protection during the daytime would drive the sensor cost and weight way up compared to a system designed exclusively for nighttime operation.

It was decided that the requirement for daytime operation would not be allowed to drive the sensor design but rather the requirements were applied strictly only at night. Having said this however, a great deal of effort on this program was focused on maximizing daytime performance. The results of this effort are discussed in section 6.0.

3.0 SYSTEM ARCHITECTURE

The next step was to more clearly define the system architecture. This is described using the functional diagram contained in Figure 2.

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

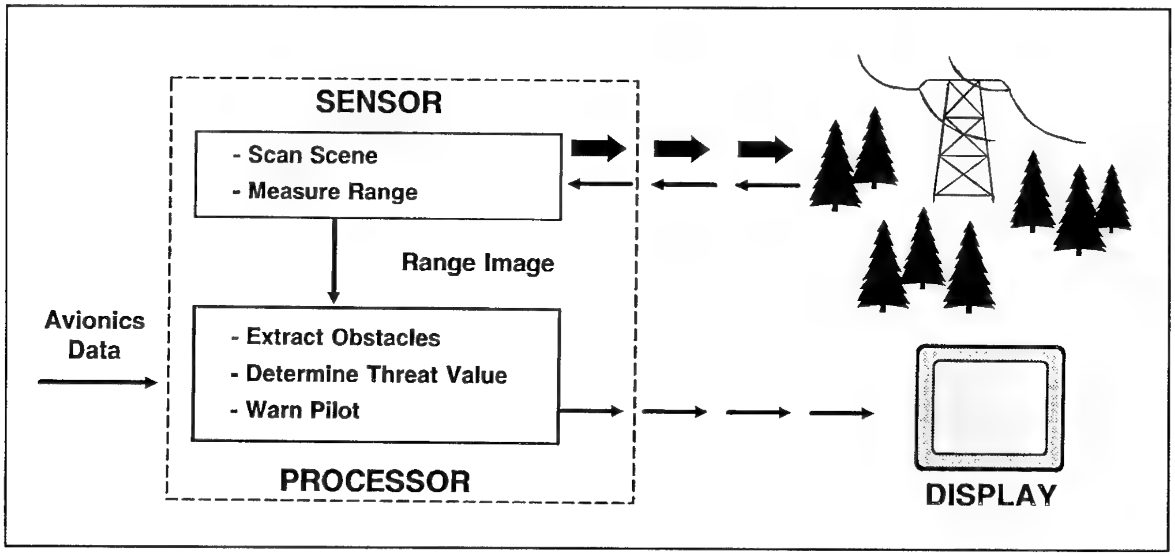

Figure 2. Functional Diagram.

The laser radar sensor scans a volume in front of the aircraft and measures range to all points within that field of regard. This information constitutes a range image from which the location of all of the obstacles can be extracted. This is done with the help of an image processor and specially designed obstacle detection algorithms. The system then uses the avionics data from the aircraft to update obstacle location between scans.

But it doesn't stop there. In order to minimize pilot workload, the processor evaluates each obstacle to determine for the pilot which ones are the most threatening. This information is conveyed to the pilot in a simple yet intuitive way, using flight cues overlaid on his primary sensor imagery.

Numerous concepts for obstacle warning symbology were tested early in the program using experienced pilots in a flight simulator at the Aeroflight Dynamics Directorate (AFDD). Since the system had to be adaptable to all helicopters, we could not assume head tracking information was available. We needed a symbology which would indicate the location of the obstacles *relative to the aircraft* and which could be clearly interpreted no matter which direction the pilot was looking. The symbology that we finally arrived at is indicated in Figure 3. In the center is an icon which is a projection of the centerline of the helicopter. A single line is then drawn, the height of which reflects the threat value for the most threatening obstacle as a function of azimuth. The pilot's task is simply to keep the icon above the line in order to safely avoid the obstacle.

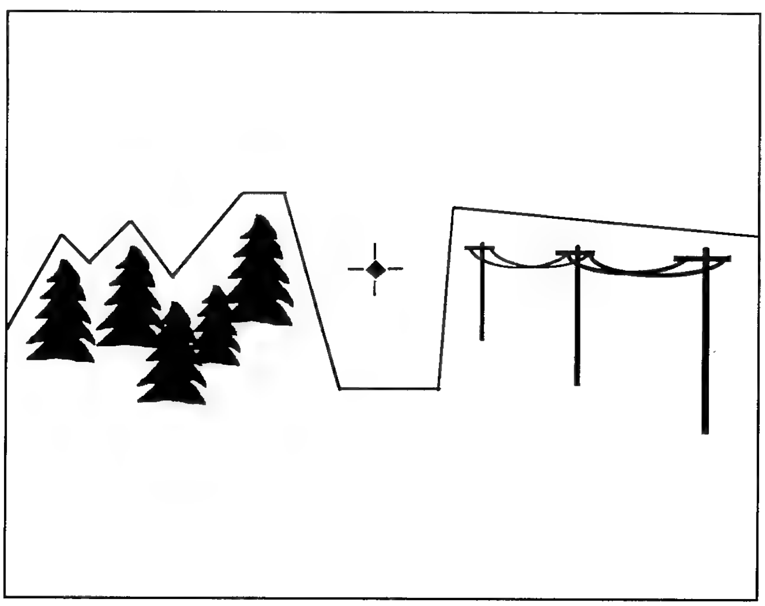

Figure 3. Warning Symbology.

4.0 SYSTEM SPECIFICATIONS

The next step was to translate the general operational requirements specified by the user into more specific, system-level requirements such as field of regard, frame time, warning range etc.. In order to accomplish this, we performed in-house modeling, analyzed accident statistics, interviewed pilots and conducted flight simulations with experienced Army pilots. The resulting specifications are listed in Table 1.

The specification for 90% aircraft protection was translated into a flight envelope consisting of speeds up to 100 knots, angular accelerations up to 2 Gs and altitudes down to 0 feet. Through modeling, the scanning parameters listed below were established to protect the aircraft over this flight envelope.

The warning range specification of 400 meters was determined through flight simulations. This gives the pilot 8 seconds of warning time at a speed of 100 knots. For warning times as low as 4 seconds, the pilot could often still avoid the obstacle, but it became a very high stress situation which was considered unacceptable for normal operations. Warning times of less than 4 seconds often resulted in crashes in the simulator.

The user required degraded atmosphere operation, but this too needed to be quantified. A minimum visibility of 2 km was chosen because, in the opinion of our pilots, this is the worst visibility under which they might still maintain a speed of 100 knots.

The most difficult obstacle to detect is a wire. For operational reasons, the sensor needed to be able to detect wires, wet or dry, at up to a 60 degree angle of incidence. The question then became, how small a wire were we required to detect under the conditions given above. Ideally one would like to detect all wires, even down to 1/8 inch in diameter. Such a specification would drive the cost and weight of the system unacceptably high, however. Instead, we examined the accident statistics to gain a better understanding of the distribution of wire sizes and the severity of the corresponding accidents. It was finally decided, in close coordination with the aviation community, to apply the requirement of 400 meter detection range to wires one-inch in diameter or larger. The combination of this target with a 2 km visibility and a terrain flight profile at 100 knots together constitute the worst case operating scenario.

5.0 SENSOR DESCRIPTIONS

A survey of industry in the late 1980s indicated that none of the prototype systems which had been developed could meet our requirements. It was our opinion, however, that the technology did exist to make such a system possible. Based on these conclusions, a program was initiated to develop an obstacle avoidance system capable of being integrated onto an aircraft and operated in real time.

Two contractors were eventually selected. Both proposed using a laser radar approach, but they relied on different laser, receiver and scanning technologies. Furthermore, while the development specification established a minimum field of regard and scan density as discussed above, there was still a lot of flexibility within these requirements regarding the details of the scan pattern and the processing and display of obstacle information. The individual contractors were responsible for establishing these parameters as part of the design process. The two systems which were developed vary significantly in these respects, and we have learned a lot from these differences.

Flight Conditions	speed	up to 100 knots
	acceleration	up to 2 G's
	altitude	down to 0 feet
Scanning	field of regard	
	elevation	20 degrees, minimum
	azimuth	30 degrees, minimum
	frame time	0.75 seconds maximum
	scan density	contiguous in 1D, gaps < 25 mrad
Range Performance	warning range	400 meters, minimum
	blind range	50 meters, maximum
	range resolution	20 meters
Atmospheric Conditions	visibility	2 kilometers, worst case
Target Parameters	wire diameter	1 inch
	angle of incidence	60 degrees

Table 1. Specifications for an Obstacle Avoidance System

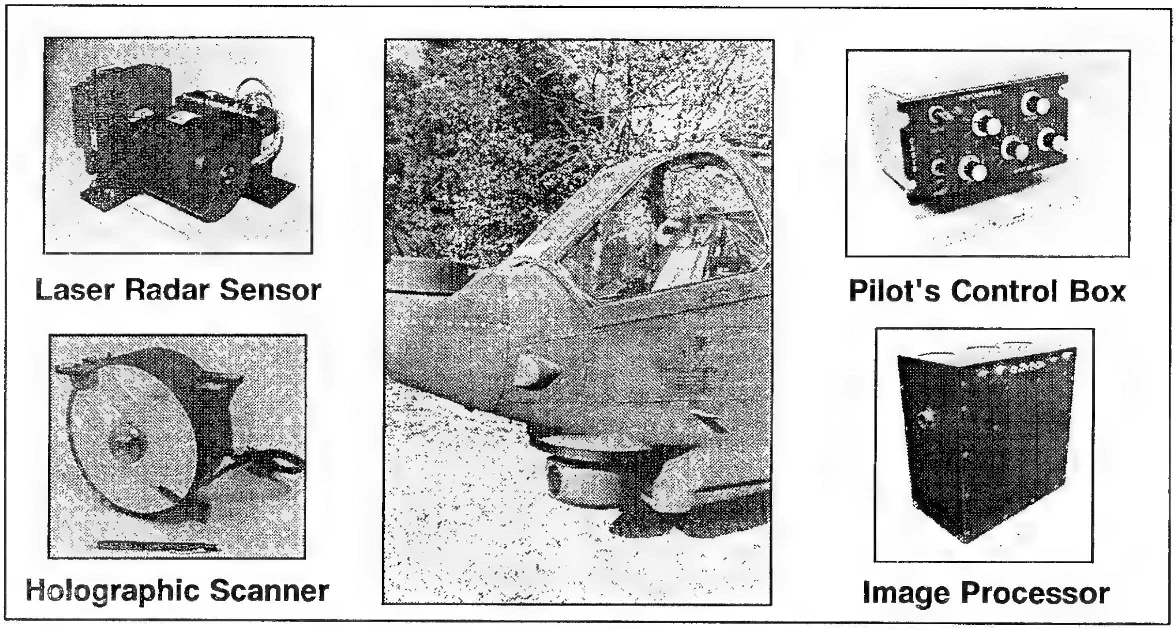

Figure 4. Components of the Northrop OASYS.

5.1 Northrop OASYS

The various components of the Northrop system are shown in Figure 4. The ladar sensor and holographic scanner are contained in the turret which has been installed under the chin of a Cobra aircraft. The data from the sensor is passed to the processor which is contained in the ammunition bay. This processor generates a warning symbology which is mixed with the PNVS FLIR imagery and displayed via the pilots' IHADDS system. A control box is installed in the cockpit to enable the pilot to vary the parameters which drive the warning symbology.

A schematic of the ladar sub-system is shown in figure 5. The source consists of a pair of 1 mm wide GaAlAs laser diode stripes produced by Spectra Diode Laboratories. These stripes are placed back-to-back, attached to a thermo-electric cooler, and placed in a hermetically sealed package. A series of lenses and prisms first collimate then expand the laser beam. The highly polarized light then passes unaffected through a polarizing beam splitter cube. Attached to the end of the beam splitter is a quarter wave plate which converts the light to a circular polarization.

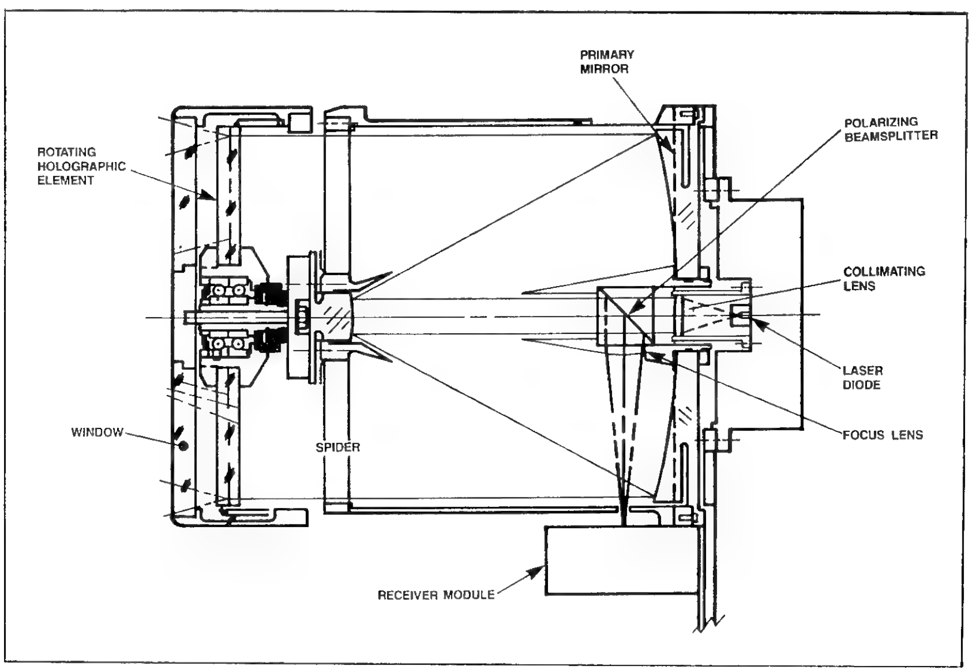

Figure 5. Ladar subsystem.

This light then passes through an on-axis, afocal telescope which expands the beam to six inches with a central obscuration two inches in diameter.

The return signal passes back through the telescope parallel to the optical axis. The waveplate then takes the circular return (assuming little polarization change on reflection from the target) and converts it to horizontally polarized light which is then deflected into the receiver by the beam splitter. Optics in the receiver focus the beam onto a silicon avalanche photodiode detector with an active area of 0.5 mm^2. The receiver path contains a narrow bandwidth filter to eliminate as much solar background noise as possible.

Scanning is achieved via a rotating holographic wedge which deflects the beam through an angle of 12.5 degrees and scans it in a circle. The entire assembly is then slewed in azimuth through 25 degrees, producing a spiral scan pattern which covers a field of regard of 25 x 50 degrees. In order to scan this area in the required frame time with maximum scan density, the pulse repetition rate must be as high as possible. 100 kHz was considered to be the maximum feasible repetition rate for the diode laser source. This allowed Northrop to reduce the scan gaps from the 25 mrad specified to just over 5 mrad. To achieve this, the holographic wedge rotates at a rate of 6600 rpm. The resulting scan pattern is shown in Figure 6.

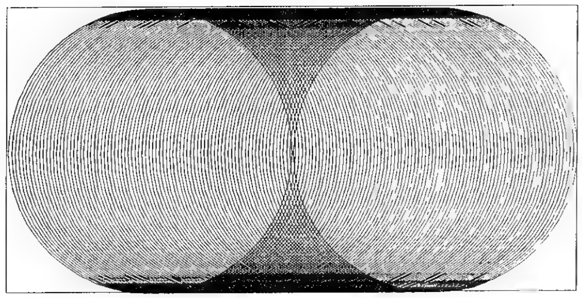

Figure 6. Northrop OASYS scan pattern.

When the aircraft enters a turn, we have the option of using the avionics data to adjust the scan rate, keeping the gap size constant relative to inertial space.

Based on the scan pattern and the planned algorithm approach, it was determined that the probability of false alarm had to be less than 10^{-4} per 5 meter range bin. The probability of detection had to be approximately 95%. These values correspond to a signal-to-noise ratio (SNR) of approximately 5.6. A number of trade studies were performed to optimize the remaining system parameters to achieve this SNR against a one-inch wire at 400 meters in the worst case operating scenario described above. The resulting system parameters are summarized in Table 2.

Transmitter	Wavelength	850 nm
	Peak Power (at source)	100 watts
	Pulsewidth	70 nsec
	Pulse Repetition Frequency	64 kHz average, 100 kHz max.
	Efficiency	
	Beam Shaping	0.67
	Optics Transmission	0.64
	Beam Divergence	1.7 mrad
Receiver	Aperture Size	6 inch
	Instantaneous Field of View	2 mrad
	Optical Filter Bandwidth	10 nm
	Efficiency	
	Optics Transmission	0.82
	Filter Transmission	0.7
	Electronic Bandwidth	7.5 MHz
Scanning	Field of Regard (EL x AZ)	25 x 50 degrees
	Number of Pixels per Frame	48,000
	Number of Circles per Frame	83
	Maximum Gap Size	5 mrad

Table 2. Characteristics of Northrop OASYS

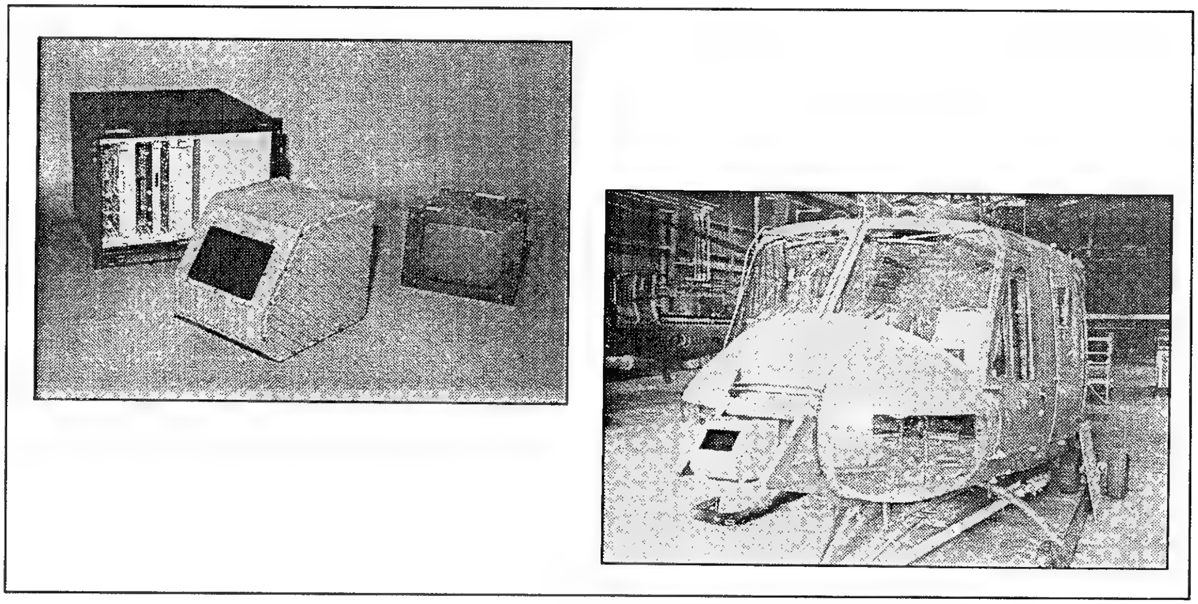

Figure 7. Components of Fibertek HLR.

5.2 Fibertek Helicopter Laser Radar (HLR)

The Fibertek HLR system consists of a sensor pod, a VME based computer and an operator's control panel. These components are indicated in Figure 7. Other components not shown include data collection hardware, power conditioning and laser cooling systems. The pod is mounted on the nose of a Huey aircraft and the warning symbology is displayed on monitors in the front and back of the aircraft.

Figure 8 shows a diagram of the sensor pod. The pod contains the laser transmitter, the receiver, the scanner, and associated support systems, all in an environmentally sealed housing.

The source consists of a 1.047 micron Nd:YLF laser pumped by 15 watt, CW, diode arrays operating at 796 nm. The laser is cooled using thermoelectric coolers, a circulating fluid and a heat sink. The laser cavity is Q-switched to give 5 nsec pulses at a rate of 15 kHz. The wavelength of the output is then shifted to 1.54 microns using a KTP crystal as an optical parametric oscillator. The resulting pulses contain 70 μJ of energy at 1.54 microns, although as much as 100 μJ can be obtained if needed. The final output beam is 5 mm in diameter and passes through a small tube which prevents backscatter into the receiver.

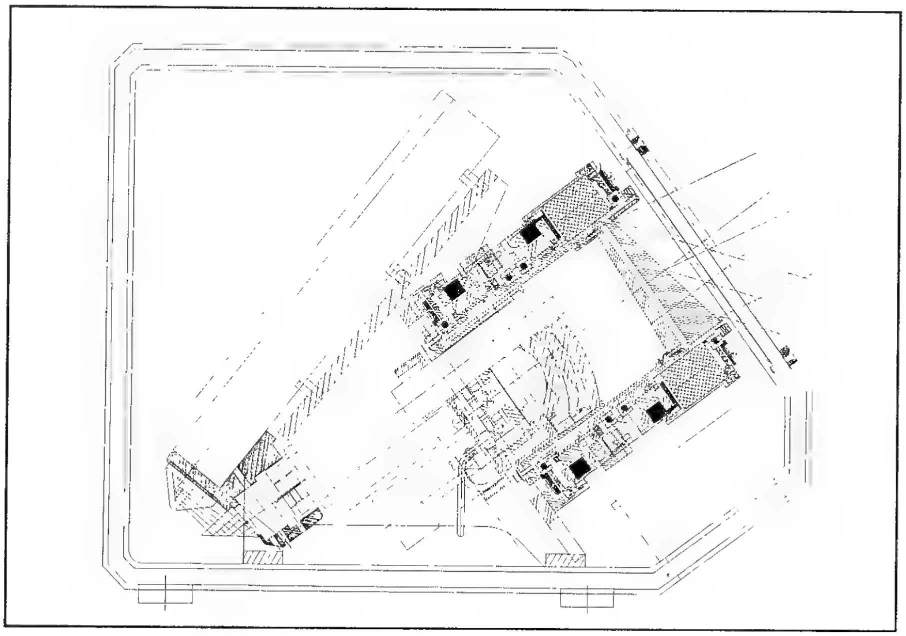

Figure 8. Details of Fibertek HLR sensor.

After striking the target, the return pulses are collected over a 2.5 inch diameter receive aperture. A series of lenses are then used to focus the energy onto a temperature stabilized InGaAs avalanche photodiode. The detector-preamplifier combination has a 50 MHz bandwidth to accommodate the short pulselength. A narrow bandwidth filter is used to eliminate solar background noise.

The scanner uses two silicon prisms, one rotating continuously at a steady speed to produce a conical scan, and the other oscillating back and forth to translate this loop along an arc. Together, the prisms create the cycloidal scan pattern shown in Figure 9. This pattern consists of 16 circular loops which cover a field of regard of 40 degrees in azimuth and 30 degrees in elevation with a maximum spacing of 25 mrad between loops.

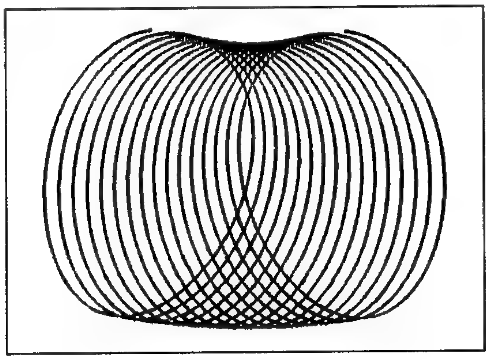

Figure 9. Fibertek HLR scan pattern.

The advantage of the 1.54 micron wavelength is that a higher signal-to-noise ratio can be achieved with a smaller receive aperture while remaining eyesafe. This helps at least in part to compensate for the fewer number of pixels, since noise can be almost completely eliminated by the proper setting of the threshold. For this design, the SNR against a 1 inch wire, 60 degrees off axis under 2 km visibility conditions at night is calculated to be 100. A complete listing of the parameters of the HLR system is contained in Table 3.

6.0 FLIGHT TESTING

The Northrop sensor was first installed on the Cobra helicopter in the spring of 1993. Over the past year and a half, we have completed close to 40 test flights totaling over 100 hours of flight time. The system has matured greatly over this time period and many lessons have been learned. The Fibertek HLR system was installed on the Huey aircraft just this past spring (1994). We have already learned a great deal from this system as well, and we are now entering a demonstration phase for both systems. Some of the lessons learned are discussed below.

6.1 Sensor Level Performance

On an individual pixel level, both systems performed more or less as expected, achieving the SNR goals established during the design phase. Of more importance, however, is the performance of each system as a whole, including algorithms, since this determines the range at which the pilot receives the obstacle warning. As already discussed, the Fibertek system has a low sampling density but a high signal-to-noise ratio. Experiments have verified that the optimum performance for this system is obtained when a high threshold is set and virtually all noise is eliminated. This still leaves a high enough signal-to-threshold ratio to get reasonable detection ranges. The sensor is then limited by how well the algorithms can pick out a wire or pole based on very few returns.

Transmitter	Wavelength	1.54 microns
	Energy per Pulse	70 μJ
	Pulsewidth	5 nsec
	Pulse Repetition Frequency	15 kHz
	Efficiency	0.94
	Beam Divergence	2 - 4 mrad
Receiver	Aperture Size	2.5 inches
	Instantaneous Field of View	4 mrad
	Optical Filter Bandwidth	40 nm
	Efficiency	0.63
	Electronic Bandwidth	50 MHz
Scanning	Field of Regard (EL x AZ)	30 x 40 degrees
	Number of Pixels per Frame	11,000
	Number of Circles per Frame	16
	Maximum Gap Size	25 mrad

Table 3. Characteristics of Fibertek HLR.

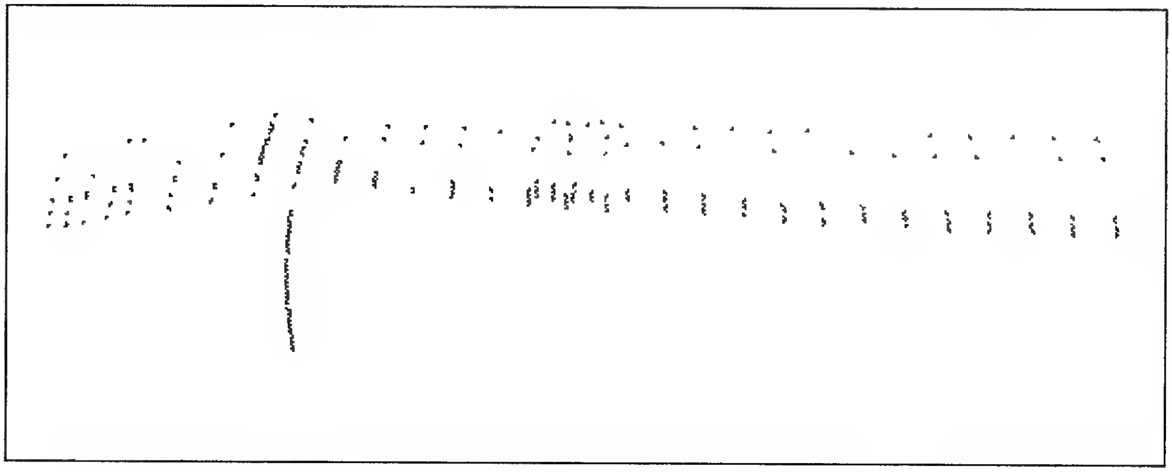

Figure 10. Image of tower and wires taken with the Fibertek HLR.

A typical image from the Fibertek sensor is shown in figure 10. This image corresponds to a tower with multiple sets of wires extending off in both directions. At the left edge of the image, the wires are at a range of 450 m. At the right edge, they are at a range of 300 m. This image was taken during the daytime under fairly good visibility conditions.

Northrop has designed a system which takes a more complex approach. In order to avoid the possible problem of a pole falling between scans and thus getting no returns from it whatsoever, Northrop's design team felt that a higher pixel density was necessary. After consultation with diode laser experts, Northrop concluded that pulses with the desired peak power level could be produced at repetition rates as high as 100 kHz without introducing undue risk. Another potential payoff of this higher scan density was that enough returns would be obtained from a true obstacle that it could be recognized even in quite noisy images.

Flight testing has verified that the optimum performance for the Northrop system is obtained with a much lower threshold setting to maximize range performance without introducing unwanted false alarms. After several rounds of software modifications, we were able to maintain a stable symbology with no false alarms while flying directly toward the sun without compromising the overall range performance of the system. This is illustrated in Figure 11. The top frame shows the raw image corresponding to a wire strung between two poles under bright daylight conditions. After the first step of processing, a fair amount of the noise has been eliminated, however much remains and is nearly impossible to distinguish from the valid returns off of the wire. After the second processing step, however, all noise in the sky has been eliminated while the wire returns remain. Comparison with Figure 10 reveals that the processed Northrop image is not that different from the raw Fibertek image in terms of information content. The Fibertek sensor remains somewhat sensitive to solar noise, although the algorithm for their system is still evolving.

6.2 Solar Noise Distribution

As discussed above, the Northrop system was designed to work with a certain level of noise present in the images. Initially, however, it was assumed that the noise would be fairly uniformly distributed throughout the image. It was also assumed that any variation would be characterized by the maximum noise being at the top of the image, since it would generally be solar in origin. What we discovered was that the magnitude of the noise varied by several orders of magnitude over a single frame of data. In order to extract maximum performance from the system under these conditions, Northrop has recently modified the receiver to include a rapid response, fast adaptive thresholding circuit. This change is expected to extend range performance somewhat.

6.3 Atmospheric Effects

Since integrating the systems onto the two aircraft, we have had only limited opportunity to operate under adverse weather conditions such as rain, snow, fog etc.. One interesting effect that we have noticed, however, concerns clouds. For both systems, we have seen cases where valid returns are obtained from dense cumulus nimbus clouds which happen to pass within the range of the sensors. The Northrop system seems to be able to deal with this phenomenon fairly well since it was designed to be more tolerant of noise in general. The Fibertek system is more vulnerable to this phenomenon. A growth option exists, however, in which the waveform of the return pulse would be evaluated and used to distinguish clouds from more solid obstacles, thereby eliminating this rare but undesirable phenomenon.

6.4 Man/Machine Interface

It is relatively simple to convey to the pilot the location of an obstacle in both azimuth and elevation using a single line symbology like that discussed in section 3.0. Experience has shown, however, that, while helpful, knowing the location of an obstacle in azimuth and elevation alone is not enough. Numerous accidents have occurred, not because the pilot couldn't see the obstacle, but because he misjudged the range to the obstacle. This was particularly true with

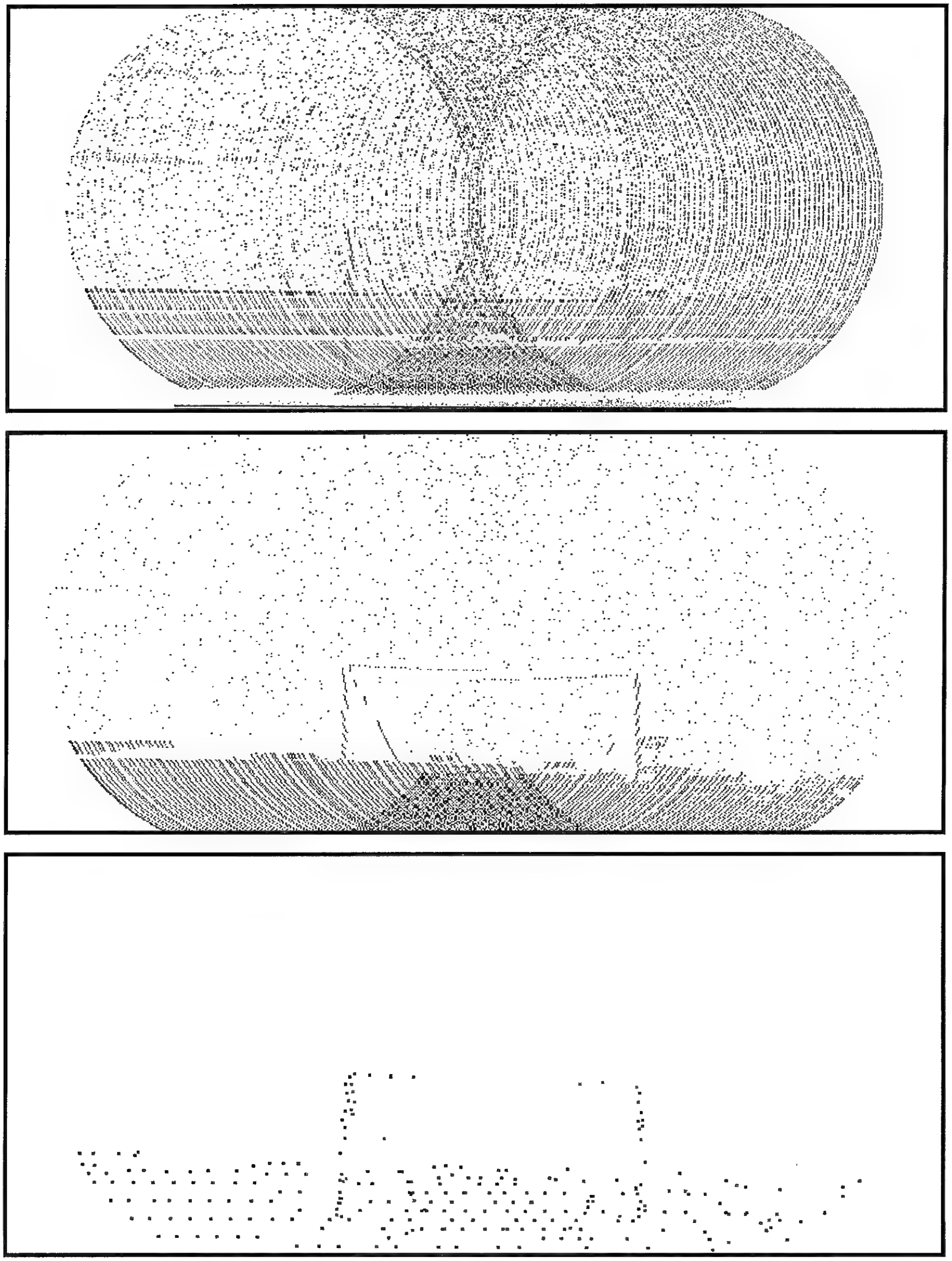

Figure 11. Image of wire strung between two poles, taken with Northrop OASYS, before and after processing.

respect to sand dunes in operation Desert Storm.

Fortunately, because the obstacle avoidance sensors are based on laser radar technology, we in fact have the desired additional information regarding range to the obstacle. The question then becomes how to display that information to the pilot on a two dimensional display without creating too much clutter or increasing pilot workload. In both systems, this issue is addressed by adjusting the elevation of the line in proportion to the aircraft's range from the obstacle. In this way we allow the pilot to stay low and hide behind the obstacle during his approach to it, giving him the cue to increase altitude only when his proximity to the obstacle makes it necessary. This approach maximizes both aircraft survivability and mission effectiveness.

There are many possible ways to implement this dynamic adjustment to the warning symbology. Both systems utilize some very clever (and proprietary) approaches, but we have really only scratched the surface in this area. What we have learned is that there is not a single, optimum way to do this adjustment. In fact, the optimum approach depends upon both the flight mission and the type of terrain involved. A mature system would still probably give the pilot some control over this feature.

Another factor which must be taken into consideration is the type of obstacle detected. Wires are of paramount importance to the pilot, because of their low visibility. Most pilots have expressed a desire to always be warned about wires as soon as the sensor detects them. Terrain is a different matter. When conditions are such that a high contrast FLIR or ANVIS image can be obtained, most pilots have stated that they would not want to be distracted by a line showing them the terrain which they can already see well. Under such circumstances, they would like to be able to set the system to indicate wires only. Both of our systems can potentially distinguish between wires and terrain, but this distinction has not been implemented into the symbology.

6.5 Avionics Data

Both systems utilize avionics data to update the position of obstacles between scans. What we have found is that the effectiveness of the warning symbology is highly dependent upon the quality of the avionics data. If the data is not accurate enough or if it has a time lag or slow update rate, you end up with multiple copies of an obstacle at slightly different locations in the data base, leading to a more cluttered display and more work for the processor. This is particularly true when turning. Accurate avionics data is also critical in order to make sure the pilot has safely cleared the obstacle before letting him drop down again. Future helicopters should have avionics data of sufficient quality for this application. For retro-fitting systems onto existing aircraft, however, it may be necessary to include inertial position measurement equipment within the sensor or to use a Kalman filter to predict aircraft position between updates.

6.6 Validation of Requirements

We embarked on this effort with a certain set of requirements for field of regard, scan density, frame time, detection range, etc. Flight testing performed to-date has not revealed any deficiencies in these areas, and the original requirements appear to be valid. We will continue to address this issue in the future as we accumulate more flight hours on the systems with pilots flying a greater variety of missions.

THE ANGLO-FRENCH COMPACT LASER RADAR DEMONSTRATOR PROGRAMME

G M Hogg
Dr K Harrison
Defence Research Agency
AVS
Bedford MK41 6AE
UK
S Minisclou
STTE France

1. SUMMARY
CLARA is an Anglo-French Compact Laser Radar technical demonstrator programme. It is a multi-mode CO_2 laser radar, the primary mode being cable and obstacle warning, with additional modes including terrain following and a range of targeting modes. The 3½ year programme will provide both France and the UK with a podded equipment in 1996. The UK will carry out fixed wing trials and France will fit their pod on a helicopter. The flight trials data being exchanged between the two countries.

2. OPERATIONAL SCENARIO
Military aircraft both fixed wing and rotary are being forced to fly lower and lower to remain screened from the enemy's surveilance systems. Fast jets are pushing to get down to 30m while helicopters are operating as low as 2-3m. In both cases the aircraft are in danger of hitting obstacles mounted on the ground. Normally the flying is carried out in VMC with the pilot relying on his eyes to pick up the obstructions and avoid them. At night NVG's are used to assist the pilot, while in poor visibility FLIR or radar are the only additional aids. However, fast jets also operate in an automatic Terrain Following mode relying only on radar or data base systems to avoid obstacles.

Obstructions vary and Fig 1 indicates the problems for fixed wing aircraft including trees, barrage balloons, pylons and worst of all electric cables. These will not be seen accurately by the TF radar and may not be on a data base. The fixed wing aircraft are really threatened by the high tension cables 1-2cm in diameter on pylons up to 60m high. The helicopters may happily fly under these but they can get tangled up in the low tension cables 3-6mm in diameter on poles 3-6m high, see Fig 2. The big problem with all types of cable is that they are not very visible to the human eye even in good visibility, and are virtually invisible at night or in poor visibility. Neither are they visible to TF radars nor will they <u>all</u> be on data bases. Thus we need a sensor which will reliably detect all obstructions which can be a threat to the aircraft in particular cables, and at a range which will allow the aircraft to manoeuver to avoid them.

3. OPTIONS
An obstacle warning sensor could be a mm radar or laser radar. Cables are the biggest technical problem due to their small cross section. To obtain good returns we need a good beam fill, and on this score alone lasers win. mm radars have other problems against cables due to their cylindrical shape and small size with respect to the sensor's wavelength. Hence we need an OWL, Obstacle Warning Laser.

4. LOCUS
In the UK, GEC produced a private venture equipment based on a CO_2 (Carbon dioxide) laser called LOCUS - Laser Obstacle Cueing System, see Fig 3. The RAE, now the DRA, supported its development with flight trials in both their HS 748 flying laboratory, see Fig 4, and on their Tornado. At the end of the trials the DRA produced a short video to show results obtained during the trials. This was shown during the presentation and it demonstrated that the CO_2 laser reliably detected both the individual high tension cables, (see Fig 5) as well as the pylons, chimneys etc and that they could be separated from the background. However LOCUS was not designed as an operational system and needed considerable further development. Hence the birth of CLARA or daughter of LOCUS.

5. CLARA
CLARA, a Compact Laser Radar, is an Anglo French Technical Demonstrator Programme (TDP) for a multi-mode laser radar, based upon CO_2 technology controlled in UK by the DRA and in France by STTE part of DGA. CLARA's prime mode is as an Obstacle Warning Laser (OWL) to support fast jet operations at 100 ft (30m), and also for helicopter nap-of-the-earth operations. It was considered that a complex sensor for only that role was not likely to be financially or operationally viable, and that a laser radar had considerable extra potential. Hence extra modes were added to the TDP. The operational requirements which this technical demonstrator aims to address are as follows:

- (a) Obstacle Warning
- (b) Terrain Following
- (c) Target Ranging
- (d) Target 2-Dimensional Imaging
- (e) Moving Target Indication
- (f) Target Vibration
- (g) True Airspeed

The obstacle warning and TF modes in CLARA require that they are in continuous operation both during training as well as in operation and hence eye safety is of paramount importance, unlike the current lasers used in military aircraft. In addition to being eye safe the laser should be such that it can operate into poor weather, operate at night and have a low probability of being detected by the opposition. All these requirements we believe will be met by CLARA because of the choice of frequency of the laser, namely carbon dioxide which also happens to coincide with that of 8-12μ FLIRs so that an operational installation would have the advantage that the optical window required by FLIR could also be used by a CO_2 laser.

6. CHOICE OF LASER
The choice of laser is fairly critical to the successful outcome of this demonstrator in that it must operate into poor weather, be eye safe, be pulsed at a very high rate and be relatively immune to detection. The current lasers used in aircraft are Neodymium-

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

YAG operating in the near infra-red band at 1.06μ. These are extremely dangerous to the human eye, and suffer the same order of atmospheric attenuation as the visible band. They also have a very low pulsing rate and hence are totally unsuitable for this application.

Fig 6 shows the relative atmospheric attenuation of optical and CO_2 wavelengths in haze and fog. It is clear that the longer wavelength of the CO_2 laser allows considerable increased penetration of poor visibility than that available at optical wavelengths. The longer CO_2 wavelengths don't penetrate the human eye and hence are also eye safe. The main protection any laser has against detection is its very narrow pencil beam with extremely low sidelobes. A CO_2 laser system can be operated with hetrodyne detection, this allows the transmitted power to be much lower than needed for direct detection and hence a peak power of only a few hundred watts is required for the CLARA application, significantly reducing its detectability. Thus CLARA is based upon CO_2 laser technology.

The laser chosen for CLARA is a 'waveguide laser' which has continuous wave operation as standard, but it can also be 'Q switched' for pulsed operation. This pulsing mode can operate up to 100 KHz (prf) which is essential for cable detection. This was the type of laser used in LOCUS. This technology is very mature and hence is an extremely low risk choice.

7. CLARA MODES

Obstacle Warning Mode

7.1 Fixed Wing Operation

Aircraft flying below about 60m (200ft) will be below the height of many high tension cables. These are not visible to centimetre radar use for terrain following, nor are they very visible to the human eye. Even the pylons supporting them are often invisible to aircrew. Thus the OWL mode must reliably detect these obstacles and determine if they are horizontal cables to be overflown or vertical obstructions to be avoided laterally. CLARA's scan of high prf pulses overlap one another as indicated in Fig 7 to provide a 100% probability of illuminating the obstructions, and provide sufficient detections to provide a 99.9% probability of recognising the obstruction in time to allow it to be avoided. The cable obstructions are 1-2cm in diameter, either singly or in groups as indicated in Fig 8. CLARA will detect these in visibilities down to about 700m at the required range to allow the safe overflying of the cables using the jet's Terrain Following autopilot. This can not be less than 1km. The autopilot provides a reliable and fast reaction to obstacle detection. Manual flying at these heights and in this visibility is not expected to be an operational procedure!

7.2 Helicopters

The nap-of-the-earth operation of helicopters as well as their landing approaches have, for a long time, been a problem due to unseen power cables, both high tension and low tension, and there have been occasions, particularly at night, when helicopters coming into unplanned landing sites have run into cables. Thus the operational requirement is to be able to detect these unseen obstacles as well as trees, poles and any other obstructions which will penetrate the operational flightpath of the helicopter. The major advantage that helicopters have over fixed wing aircraft is that they fly at much lower speeds and hence the range at which they require warning of obstructions is considerably less than that of the fixed wing high speed jet. So instead of detections at 1km detections at 300m will be adequate for safe avoidance of these obstructions from an OWL point of view. A helicopter has one major disadvantage over that of the fixed wing aircraft in that the fixed wing aircraft effectively flies in a very controlled and very limited flightpath so in the short term it is close to a straight line. The helicopter, on the other hand, has a very high manoeuvrable capability and can do very high turns in both azimuth and elevation, this means that theoretically the helicopter would like to survey a hemisphere ahead of the aircraft. In practice this is not practicable. However it is unlikely that this high manoeuvrability will be used in poor visibility or at night, and hence CLARA will examine the ability to detect obstructions by scanning limited areas or volumes ahead of the aircraft, based again on its current rates of turn both in the vertical and the horizontal plane. As helicopter operation requires only relatively short range operation of the laser, the effect of weather on its performance will be considerably less than that for the high speed jet, as the atmospheric attenuation is purely a function of path length of the laser's transmission.

Helicopters have another disadvantage compared with the fixed wing in that they are relatively small, light and have relatively low payload, hence the sensors fitted to helicopters should obviously be as small and as light as is possible. CLARA at this stage does not intend to address these requirements and, to minimize the costs for the demonstrator, the aim is to produce a relatively large pod primarily designed for fixed wing installation and mount that on the helicopter. In the longer term it is expected that a different laser technology will be available for helicopter use and hopefully allow a much smaller, lighter installation. This would probably be at a shorter eye safe wavelength, say 1.5 to 2μ which would be acceptable for the shorter operational ranges required by the helicopter, even allowing for the higher atmospheric attenuation. However, the systematic aspects of helicopter operation addressed by CLARA will be equally valid.

Helicopter operation is purely manual and hence CLARA must display its detections to the crew and possibly give additional audio warnings. This aspect of the operation will be addressed by the French in their helicopter trials.

7.3 Terrain Following (TF)

The laser radar searches the volume of space ahead of the aircraft and sees the ground as well as the obstacles. The OWL mode processes the returns to extract the obstacles, but if all the returns are accepted we have a TF mode. Lasers don't have the range of cm radars and hence the CLARA TF stand alone mode will be limited to undulating terrains but will exclude rugged mountains. However if it is used in conjunction with a terrain reference TF system we have the perfect mix. The data base provides the general lie of land while CLARA fills in the cultural and obstruction overlay which is unlikely to be complete on the data base. With this combination a full TF system is provided at and above 30m set height.

7.4 Targeting Modes

Lasers are currently used in aircraft as target rangers. CLARA will provide a range of targeting modes which will be applicable to both fixed wing and helicopter operations.

7.5 Ranging

The laser can be directed onto and track a potential target using an Auto-Lock-Follow mode by marking a target on a TV format display - FLIR, or TV or Hot-Spot cuer. The laser then ranges on the target.

7.6 Moving Target Indicator (MTI)

The laser can be used in a doppler mode and hence an MTI mode is also provided by measuring its radial velocity with respect to that of the terrain.

7.7 Imaging

At present CLARA's design will provide 2-D imaging. 3-D imaging from a laser radar is possible but it is not certain what advantage this will be over 2-D.

7.8 Vibrometry

CLARA will also measure the targets inherent vibration signature. This technique is currently used from ground-to-ground or ground-to-air, but CLARA will address the air-to-ground mode. This mode has the potential of providing unique identification signatures.

7.9 True Air Speed (TAS)

For helicopters in particular, laser TAS mode is unique in its ability to measure true air speed from doppler returns from the backscatter from aerosols in the atmosphere. It also provides information to assist in missile launch predictions with measurements of wind shear along the missile's initial path.

Thus CLARA is a wide purpose sensor for low level aircraft - Fixed or Rotary Wing.

8. PROGRAMME

The TDP is a 3½ year development programme started in October 1992 and will provide 2 podded equipments in April 1996. One pod is for the UK for fixed wing trials and assessment, the other one is for France for helicopter trials and assessment. The data being interchangeable between UK and France.

The Pods are made large to reduce engineering costs - 20.5" (520 mm) diameter x 12 ft (3.6m) long.

Figs 9 and 10 show how they will be mounted on the DRA's Tornado and the French Puma. The latter is obviously not an operational installation, nor is that on the Tornado as it occupies a vital weapon station.

In production it is expected that the equipment will be miniaturized and mounted in-board. In fixed wing aircraft it would be integrated with the FLIR and use the same window. In helicopters it could be engineered with a shorter wave-length laser which would be acceptable for the shorter range requirements of the helicopters. However the fixed wing application would remain with a CO_2 laser because of its higher power and better weather penetration.

LOW LEVEL THREATS

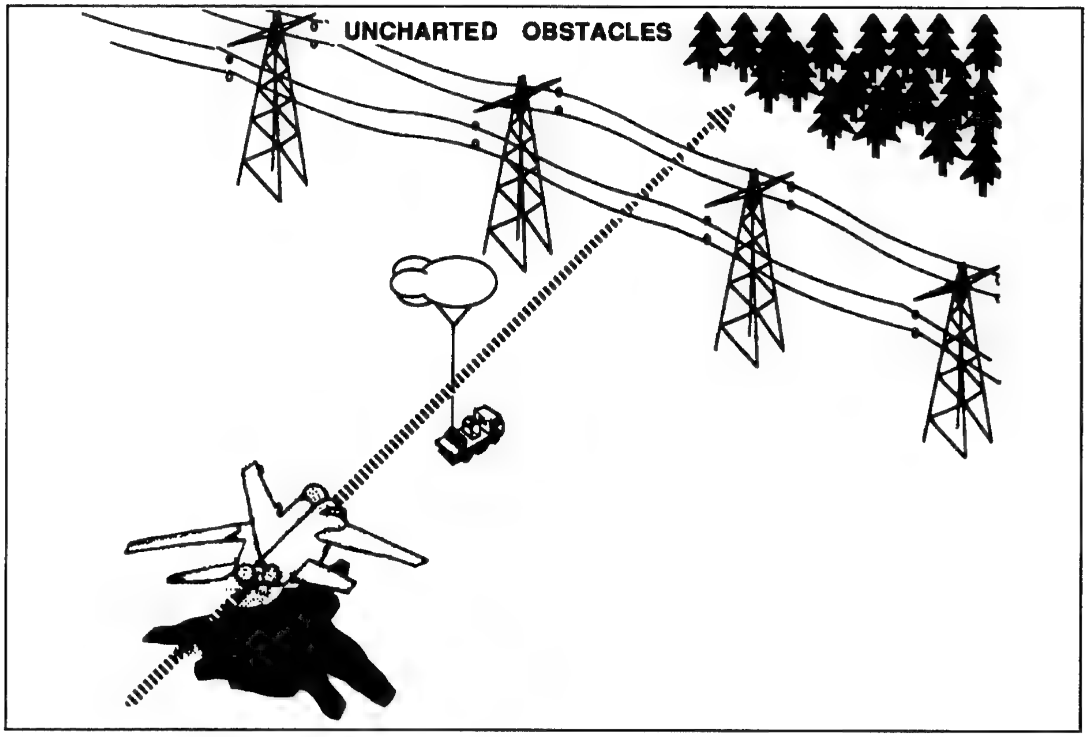

Figure 1 Fixed Wing

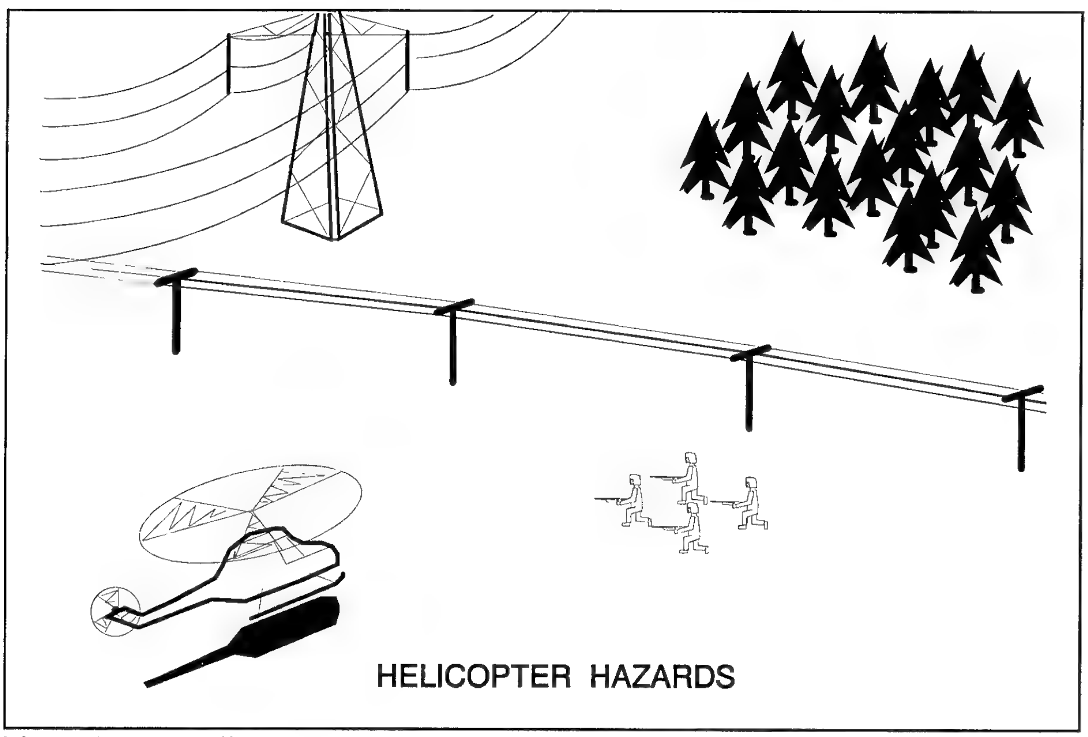

Figure 2 Helicopters

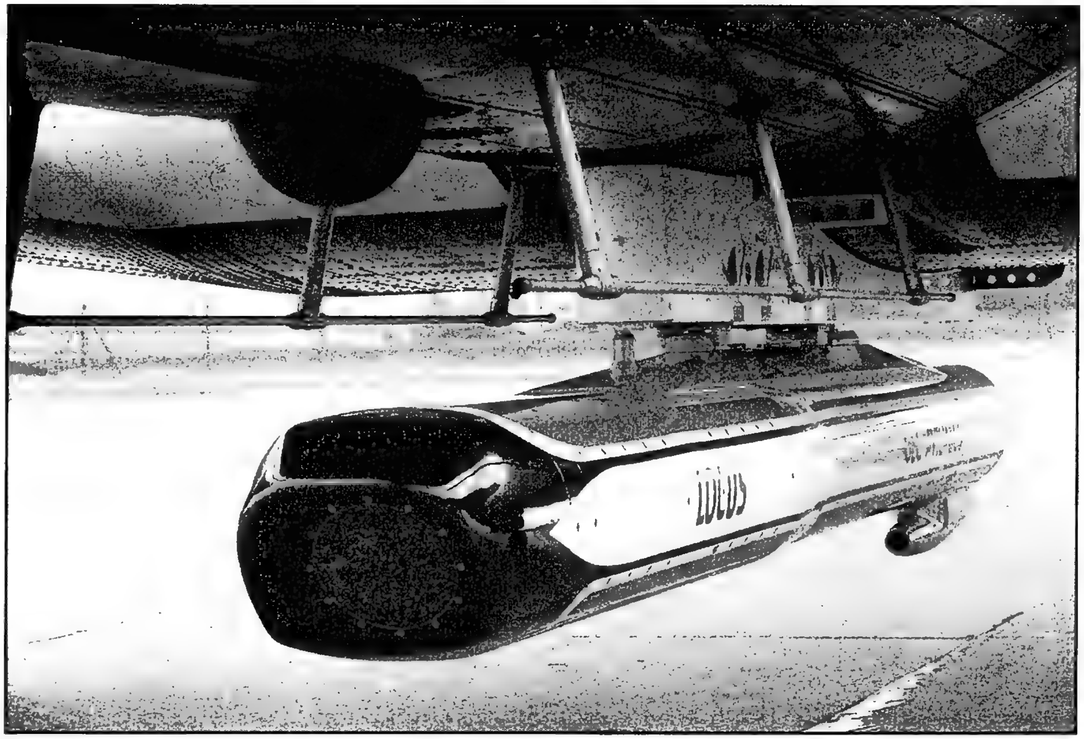

Figure 3 Locus Pod

Figure 4 LOCUS On HS748

Figure 5 Poor reproduction of a LOCUS video showing laser returns from the cables

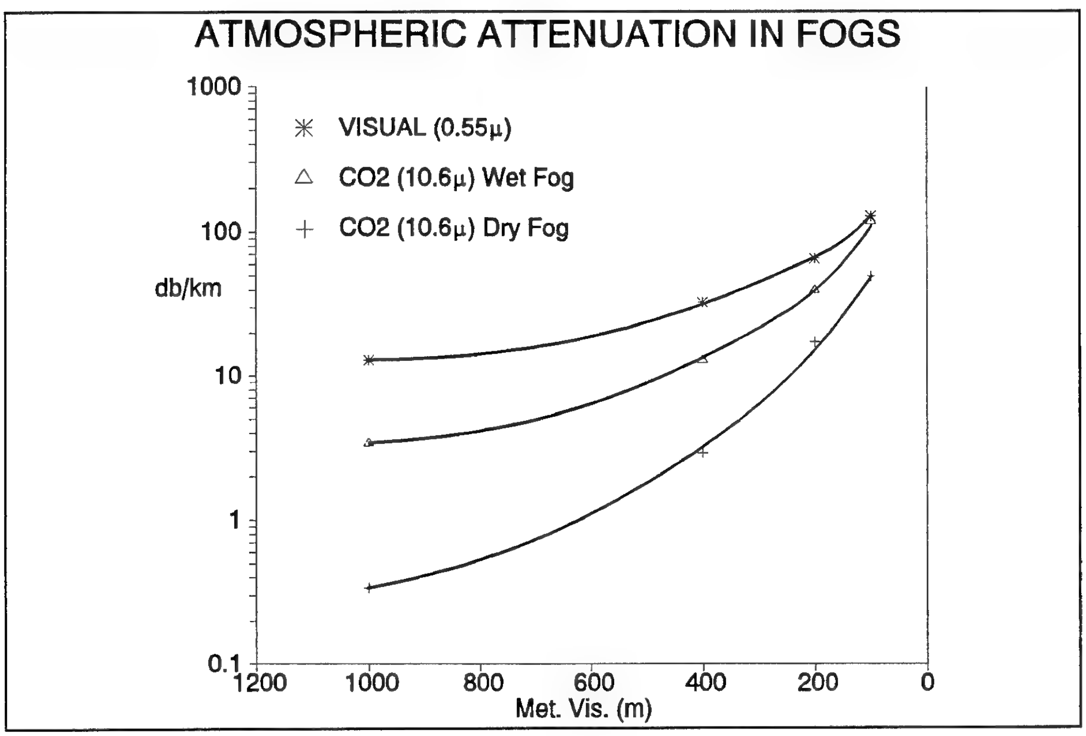

Figure 6 Fog Penetration

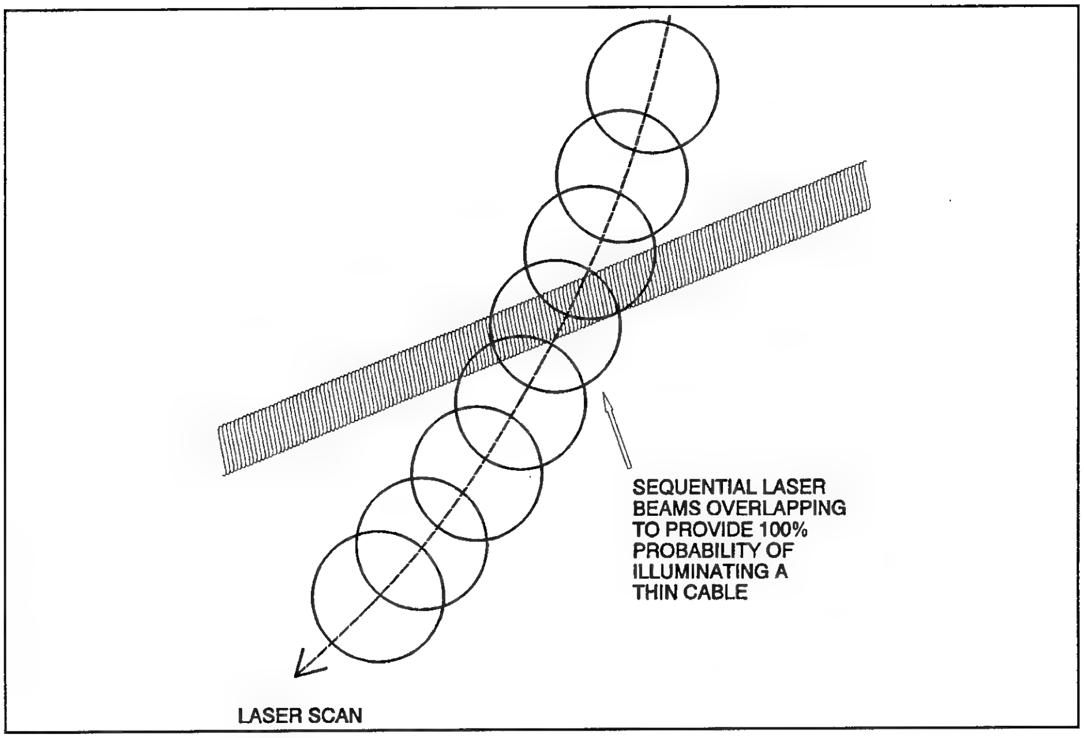

Figure 7 Cable Scanning By OWL

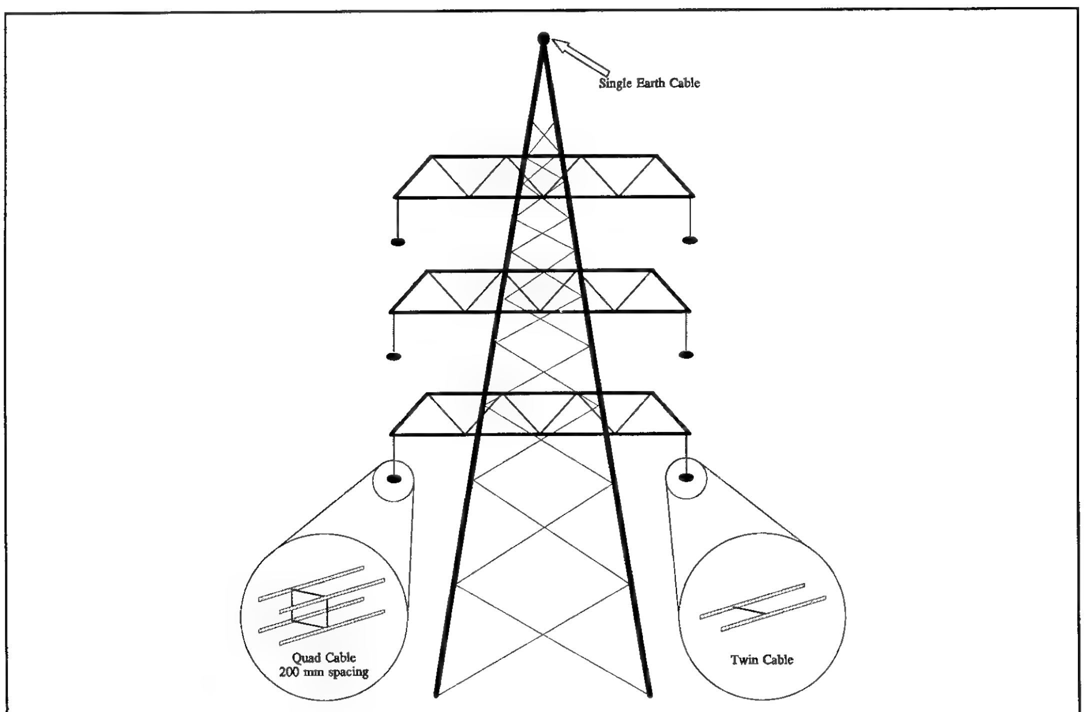

Figure 8 High Tension Cable Configuration

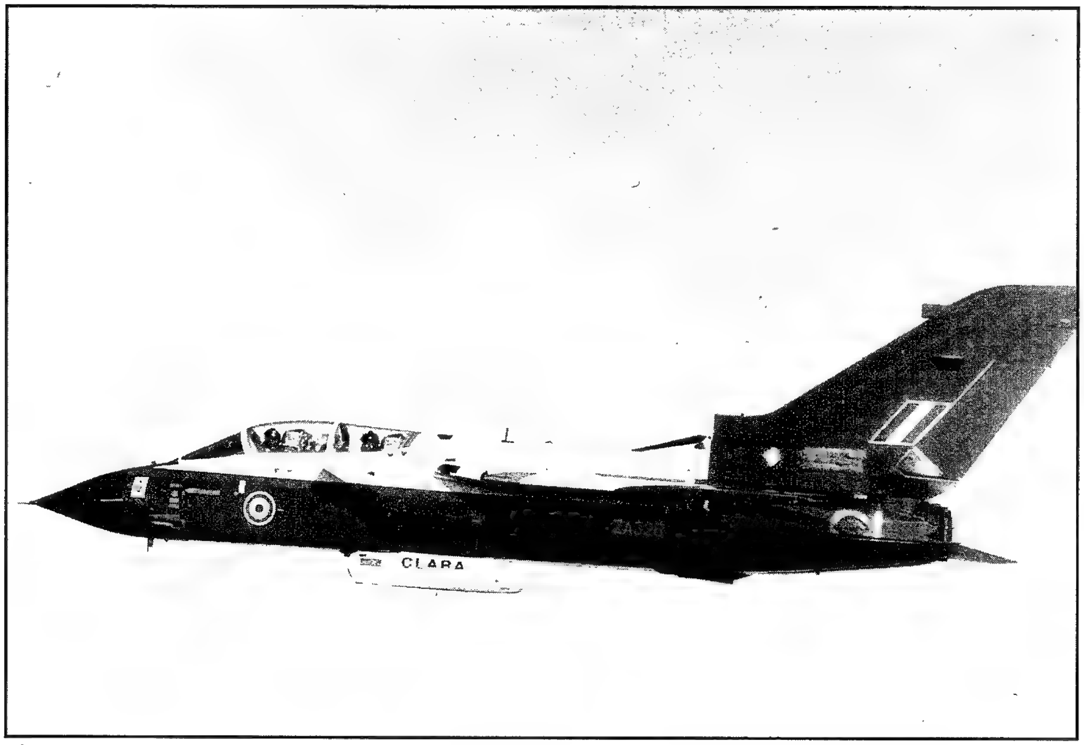

Figure 9 CLARA On Tornado

Figure 10 CLARA On Puma

Fixed Wing Night Attack Missions: Assessment in a Flight Simulation Environment

Magg. G. Arpaia - Cap. E. Scarabotto
Reparto Sperimentale Volo
Aeronautica Militare
Aeroporto di Pratica di Mare - Roma - Italia

Ing. M. Spinoni
Alenia Aeronautica
corso Marche 41
Torino - Italia

SUMMARY

Transforming a dedicated daytime attack aircraft in an effective night-attack weapon system requires the evaluation of different aircraft and navigation/attack sensor configuration options.

Flight Simulation has been considered an appropriate tool to enable preliminary evaluations of these different options.

This paper illustrates the results of a first series of evaluations performed on the Alenia Aeronautica AM-X Flight Simulator with participation of Italian Air Force pilots and engineers to evaluate some proposed options for a night-attack version of the Alenia-Aermacchi-Embraer AM-X aircraft.

INTRODUCTION

In the last years a number of night attack versions of aircraft originally designed for daylight operations has been developed.
In the process of deriving an effective night attack weapon system from a day-light version, at a certain stage it is required to make two basic choices:

- select the optimized architecture of dedicated navigation and attack sensors;

- select a single-seat vs a twin-seat configuration.

Making the most appropriate decision requires the capability of evaluating different aircraft and sensors configurations together with the possibility of developing effective operational procedures.

Italian Air Force is operating the Alenia-Aermacchi-Embraer AM-X attack aircraft specifically developed for day-time CAS/BAI missions: extending the operational envelope to enable night-time VFR attack missions is being considered.

For this scope different aircraft and sensors configurations derived from the actual AM-X have been proposed. Although other available examples have been considered, it has been decided to perform an autonomous investigation in order to gain an original experience without being influenced by solutions made by others. At the end of this activity the resulting configurations will be critically compared with existing or being developed ones.

Availability of the AM-X Development Flight Simulator at Alenia Aeronautica Torino facility has suggested to perform a comparative evaluation of the different configuration proposals in a simulated operational scenario.

A team of Italian Air Force and Alenia pilots and engineers has been established to define and perform these evaluations, which results will allow to suggest a number of configuration options. These options will form the basis for further design activities if and when a decision on developing a night-attack version of AM-X will be taken, in order then to proceed to more comprehensive in-flight evaluations.

To perform the necessary simulation activities, available AM-X Flight Simulator hardware and software has been augmented by specific developments to achieve a realistic sensors and tactical scenario simulation.

The activity is still in progress and results collected so far demonstrate the usefulness of this development approach and confirm the value of a strict working cooperation between the users and the engineers in the design of an advanced weapon system.

OPERATIONAL REQUIREMENTS

The AM-X dedicated attack aircraft is being currently operated in the Italian and Brazilian Air Forces in the Close Air Support (CAS) and Battlefield Air Interdiction (BAI) as well as in armed reconnaissance primary rôles. A secondary capacity is Offensive Counter Air and Air

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Defence in limited areas.

A two-seat version has also been developed to be utilized in operational conversion units.

These missions are mainly performed in day-light conditions at low level heights and high subsonic speeds. Primary attack sensor is the FIAR Pointer radar ranging equipment, with radar and baro altimeters being utilised for weapon aiming computations in a secondary mode.

Armament includes up to 3,800 kg (8,500 lb) payload, two AIM-9L Sidewinders Air-to-Air (A/A) missiles and one M61 20 mm internally mounted gun (Brazilian version is equipped with a pair of 30 mm DEFA guns).

The aircraft configuration and the onboard systems have been designed from the inception to allow a reasonably easy evolution whenever the modification of the operational scenario should have required it.

In the last years a particular attention has been given to the necessity of expanding the AM-X rôle to the capacity of operating also in night-time conditions. This requirement derived basically from the analysis of possible realistic operational theatres where it appeared that a 24 hours a day presence is almost a necessity.

Since in the Italian Air Force it is already available the Panavia 200 MRCA Tornado aircraft capable of all weather long distance penetration operations, a first consideration has been to avoid any possible cost-ineffective superimposition of rôles. For these reasons it has been considered that a night-attack version of the AM-X should be mainly dedicated to night VFR missions, leaving all-weather operations to the Tornado aircraft.

On the other hand, analysis of other potential customers requirements has shown an interest in a weapon system capable of day- and night-attack operations but without either the complexity (and associated high costs) of more sophisticated all-weather aircraft or the intrinsic lower performances of attack versions of trainer aircraft.

In particular a preliminary operational analysis suggested to concentrate the attention on both the CAS and BAI rôles, with the intention of producing a number of configuration options for each rôle from which it shall be possible in the future to derive the best option to satisfy the operational needs of the customer at that time.

DEVELOPING THE NIGHT-ATTACK AM-X

A pre-feasibility study has then been conducted within the AM-X consortium companies to develop a number of configuration options for the derived night-attack version of the AM-X.

Both a single-seat and a twin-seat versions have been studied, each of them with a different number of options as far as nav/attack sensors are concerned.
This preliminary activity concluded that different options are apparently adequate for fulfilling operational requirement. However, different levels of complexity associated to increasing development and production costs are possible.

In addition, a mission analysis has been performed to better define crew tasks in all phases of the considered CAS and BAI missions together with giving a preliminary definition of number and types of cockpit displays and controls. Also initial automation level requirements have been evaluated.

This analysis concluded that both single- and twin-seat version could be theoretically be adequate, but it also indicated that in a single-seater allocation of functions to the single crew member should have highly increased workload.

At the end two basic configurations have been retained for further in-deep evaluation:

- a single-seat version with Night Vision Goggles (NVGs) compatible glass-cockpit, raster/stroke Head Up Display (HUD), map generator, multi-mode radar, internally mounted not-steerable navigation Forward Looking Infra Red (FLIR) and an IR targeting /laser designation pod;

- a twin-seater with the second crew member acting as Navigator/Weapon System Officer (N/WSO) and the same sensors and displays options as the previously described single-seater.

For both versions use of NVGs has been considered an option.

At that particular point in the development process a trade-off between a single- versus twin-seat versions appeared necessary.

This trade-off analysis was necessary to answer questions like:

- which are the nav/attack sensors necessary for transforming a day-light attack aircraft to an effective night-attack one?

- with these sensors, is it possible to effectively perform the considered missions retaining a single-seat configuration?

- if it is not, what are these limitations? Can they be removed developing a twin-seat version? Is there a single-seat configuration that allows an acceptable degree of operational effectiveness?

It became soon clear that such an analysis should have required the strict cooperation of both Air Force and industry pilots and engineers: in fact, this cooperation has already demonstrated its high value in other programs. Furthermore, it became evident that availability of a tool like the AM-X Flight Simulator at the Alenia Flight Simulation Center in Torino would have enabled to effectively perform significative evaluations of the different considered design options.

In fact, use of an engineering development Flight Simulator gives some advantages when performing a preliminary design trade-off study. In particular:

- use of the Flight Simulator enables individuation of all operational aspects that could make ineffective a particular configuration option. In fact, although simulation can not fully replace flight test activities, it is highly effective in reducing options to a manageable number to be subsequently flight tested. This at the end leads to an overall development cost reduction;

- use of the Flight Simulator enables performance of a high number of low height mission sorties at night with no risk for the aircraft, the crew and the population/environment. In addition also high risk tasks can be evaluated in complete safety;

- the AM-X Flight Simulator has been conceived from inception to be quite easily modifiable in order to enable evaluation of different system architectures.
In addition flight simulation has the intrinsic advantage of allowing flexible working sessions where different configuration parameters can be changed in realtime increasing the evaluation effectiveness.

However, there are some acknowledged limitations of using a Flight Simulator for night, low level flight (see also ref. 1). These basically are:

- state of the art computer imagery projected inside a dome still provides limited height and speed cues for highly realistic low level flight simulation;

- fully realistic simulation of NVGs and FLIR imagery (including for example NVG visual saturation due to flares and dynamic interaction of objects thermal radiation on FLIR) has been considered too demanding and it has been simplified to more relevant visual characteristics;

- fatigue effects on pilot due to prolonged use of NVGs during manoeuvred flight has not been simulated.

Despite these limitations, it has been judged that using the AM-X Flight Simulator in this phase of the activity was adequate to perform cost-effective evaluations of different aircraft and sensors configurations.

THE AM-X FLIGHT SIMULATOR

The AM-X Flight Simulator simulator has been and is being extensively used in the course of the AM-X project to support the development of the flight control system, avionic system, displays and controls design as well as in the training of Italian and Brazilian Air Force pilots transitioning to the aircraft (see ref. 2 and 3).

The basic configuration layout of this simulator has been considered as adequate for the purpose. However a number of specific modifications was required, both in the simulator software and hardware.

Fig. 1 shows the AM-X Flight Simulator layout with indication of the modifications / upgradings specifically implemented for this activity; they are detailed in the following paragraphs. All hardware and software modifications have been developed within Alenia.

Modified Cockpit layout

On the AM-X Flight Simulator a cockpit resembling the current production layout is available. In order to reduce costs, it has been decided to avoid any major modification to the cockpit displays and controls.
However, to perform the required activities a supplementary colour multi-function display (MFD) with relative controls has been added.
The original MFD is used for presentation of targeting pod video, while on the additional display it is possible to present radar and situational awareness (i.e. navigation plus map plus threat data) formats.
In addition, the raster/stroke wide-angle (30 x 20 deg Field Of View - FOV) HUD necessary for the navigation FLIR has been simulated with projection of computer generated FLIR video plus specifically developed symbology on the simulator dome in front of the cockpit (see also next paragraph).
Hands On Throttle And Stick (HOTAS) controls have been modified to satisfy new sensors and weapon system controls requirements.

Navigation FLIR
Simulation of external world IR image as seen by a navigation FLIR has been developed using the available General Electric Compuscene IV Computer Generated Imagery (CGI) system. The 32 levels of gray scene is then projected on the simulator dome in front of the cockpit.

NVGs Emulation
To enable the evaluation of using typical 3rd Gen NVGs several options have been considered, including the use of a head tracker to control a slewable projector.
However, to reduce costs, a simple but effective solution has been found in obscurating the transparent visor of a standard HGU-2A/P flight helmet and creating two port-holes in front of the pilot eyes. With this facility, associated to the projection on the simulator dome of a computer generated external world image (120 x 60 deg FOV) of similar characteristics as seen through NVGs, it has been possible to emulate the FOV limitations associated to the operational use of these devices.

Multi-mode Radar Simulation
In order to evaluate the option of integrating a multi-mode radar in a night-attack version of the AM-X, avoiding the complexity of a realistic simulation of a particular equipment, it has been considered adequate to develop a simulation model of a typical multi-mode radar (see Fig. 2).
Major aim has been to provide a radar simulation capable of allowing realistic pilot's workload assessment during typical radar operations. For this scope a number of radar modes and relative moding have been developed, including up to now:

- A/S ranging;
- Ground Mapping (GM);
- Terrain Avoidance (TA);
- Contour Mapping (CM);
- A/A ranging (gun, AIM-9L).

Other advanced modes (e.g. Doppler Beam Sharpening) have not yet been simulated, as well as A/A modes that are not considered relevant for this phase of activities.
The simulation included a number of HOTAS and multi-function controls on the radar display as well as dedicated radar controls on the left hand cockpit console.
The most outstanding problem that has been solved during this activity is the landmass simulation: realistic simulated operational use in the Flight Simulator requires availability of radar formats in accordance with the terrain data-base available in the CGI system. This includes radar tracks of ground objects.
The activity of developing this landmass simulation has been a thorough one, and it has been made possible by using a high-performance Silicon Graphics VGXT 420 workstation and in-house developed software.

Targeting Pod Simulation
A simulation of a typical laser designation pod with IR camera has been developed using the Compuscene IV CGI system.
Simulation includes generation of IR video to be presented on a cockpit MFD (see Fig. 3), operating modes such as autonomous tracking capability and laser ranging capability.
HOTAS controls have been modified to include targeting pod specific requirements.

Situational Awareness Display
As seen previously, one colour MFD is used mainly for presentation of a specifically developed Situational Awareness display with presentation of a geographic map with superimposed navigation data, threat as well as Radar and Missile Warning indications (see Fig. 4).
The vectorial-type map has been developed to allow presentation of a map of the territory congruent with that available in the CGI system data-base. Cultural data have been superimposed and can be altered whenever it is necessary.

Tactical Scenario
To achieve a significant result in this activity, an essential requirement has been considered the capability of simulating a realistic operational tactical scenario.
To this purpose a typical operational theatre representing, among the others, features such as enemy airports with Surface-to-Air (S/A) defense, SAM/AAA sites, ground and naval radars, ground and naval targets, enemy fighters has been implemented.
Particular attention has been paid in simulating terrain influence on ground radars detection capabilities, in order to enable effective use of terrain masking features when flying at very low heights. Also simulation of S/A and A/A missiles has been developed to evaluate probability of being hit during the mission.
An operator in the Flight Simulator control room is able to control enemy actions and trigger some events like the fire of a SAM.

Second Crew Member Station
As said previously, one of the goal of the activity is to evaluate performances of a twin-seat version of a night-attack AM-X compared to a single-seater.
Creation of a second cockpit in the AM-X Flight Simulator dome has been soon discarded on the ground of costs. However such a possibility has not been ruled out, but it could be considered only when a development activity is funded.
Also creation of a complete second crew member cockpit outside the dome has been similarly discarded.
In addition, it has been considered that for a preliminary set of trials the essential aspect was to evaluate the pilot workload "relief" made possible by the presence of a second crew member on-board.

Following these considerations it has been decided to develope a work-station in the Simulator control room where the Navigator / Weapon System Officer (N/WSO) is able to manage a number of function duplicated from the pilot's cockpit without paying particular attention to realise a cockpit-like layout.
This station is basically a computer display with a mouse plus a number of displays on which the N/WSO can control external view, HUD symbologies as well as MFD formats.

MISSION SIMULATION

A series of simulation trials has been planned for assessing low level flight and attack characteristics with different aircraft and sensor configurations.

Two operational scenarios have been developed up to now and have been used in these simulation trials:

- a CAS theatre with the AM-X flying a low level route to an orbit point where updated target data are received from a Forward Air Controller (FAC).
After receiveing these data, a very low height penetration through the FEBA up to a landing site for enemy tanks with subsequent target search and delivery of laser guided and general purpose bombs in dive or glide modality or, as an alternative, gun strafing.
After recovery, a low height return to base is flown;

- a BAI theatre with low level navigation route through the FEBA up to an off-set point in proximity of an enemy airport defended with SAMs and AAAs.
After navigation updating on the off-set point a Continuosly Computed Release Point (CCRP) technique attack is performed with toss delivery of LGBs.
Disengagement is then carried on ensuring laser illumination up to the bombs impact, followed by a low height return to base.

During the mission an operator from the Simulator control room acts on the ground and naval discovery and tracking radars, launches SAMs and conducts enemy fighters to intercept the attacking aircraft. The pilot in the cockpit is then able to counteract these threats both performing appropriate manoeuvres and releasing chaff/flares as necessary.

Weather conditions can be varied from the Simulator control room; in particular, visibility can be changed at any moment as well as introduction of wind and gusts of different strenght.

In both mission typologies, if required, navigation fixing updating could be performed during the navigation phases, using traditional on-top or radar ranging techniques as well as using the ground mapping radar or the laser ranging capability of the targeting pod. In addition target of opportunity (TOO) attacks could be performed at any moment of the mission on adequately placed ground targets.

The operational scenarios have been developed in a geographical area with different terrain features like plains, rivers, mountains and valleys, shores in order to enable evaluation of navigation performances with different sensors in different conditions.

The two above described basic missions have then been considered to be flown at different levels of complexity. Three operational parameters have been individuated to determine increasing levels of complexity in a first series of tests:

- navigation height (e.g. 500 ft, 300ft);
- meteorological conditions (e.g. fine weather, low clouds, degraded visibility);
- enemy threats (no A/A engagement, one A/A engagement).

Different levels of complexity can be achieved changing one or more of these operational parameters. However, simulation trials performed up to now have not completed all considered options but only a significative subset: completion of all tests constitutes the follow on of the present activity.

In addition, both CAS and BAI missions have been flown in both single-seat and twin-seat configurations.

DATA COLLECTION METHODOLOGY

Collection of data during and after the simulation trials has been considered one of the most complex part of this activity.

In fact, since the scope of the whole activity is the individuation of configuration solution(s) for a night-attack version of the AM-X, it has been considered necessary to derive from the tests information regarding not only the pilot workload levels but also evaluate assets like flight safety, mission effectiveness, operational procedures etc.

In order to keep things simple, and to maximise the use of the most valuable resource (i.e. the pilots' time!), a quite simple methodology has been established, postponing the use of more comprehensive statistical methods to a later phase of the evaluation.

This methodology consisted basically in the on-line recording during the mission of a number of parameters together with a video tape recording

of external world, HUD and MFDs symbology, data entry devices use. Of course also audio comms have been taped.

Recorded mission parameters include a number of flight data (e.g. height, speed, present position, Early/Late indication) as well number of crashes, "kill probability" derived by exposure to SAMs, AAAs and A/A threats, weapon delivery precision, etc.

During the mission observers sitting in the Simulator control room were able to monitor pilot's actions also via a set of TV cameras installed in the cockpit. From this direct observation it was possible to evaluate pilot's actions and procedures, in particular to assess appropriateness of pilot's manoeuvring after detection of radar or missile warnings.

In addition, post mission de-briefings have been planned for each test in order to enable pilots to express their perception of workload in the various parts of the mission together with some form of colloquial discussion with engineers in order to discriminate pros and cons of different design features.

Subsequently, an initial off-line analysis of recorded data together with de-briefing minutes has been performed to derive a consolidated set of results.

PRELIMINARY RESULTS

As already said, not all planned tests have been completed so far, so the results that are discussed in the following must be considered as preliminary and require to be confirmed after completion of the foreseen activity.

The tests conducted up to now have in any case been important in allowing individuation of a number of design hints that in our view should be carefully considered if and when a night-attack version of AM-X will start development.

In the following the most significative design and operational issues that emerged from the simulation tests are briefly discussed. In the next chapter these consideration will be considered in order to define a number of configuration options for a night-attack version of AM-X.

Terrain Avoidance

One of the most important problem in operating at night in a mountainous terrain so common in Europe is to achieve a safe terrain avoidance when flying at very low heights.

In fact, flying navigation and penetration legs at very low height (in the order of 300 ft) has been considered a firm requirement since a realistic operational scenario should in our view consider heavy enemy ground and air defences.

The tests performed allowed to evaluate a mix of sensors used to enable effective terrain avoidance both with good and marginal visibility conditions.

The majority of tests were conducted with a simulation of a fixed navigation FLIR with presentation on HUD, with and without NVGs. In some occasion these sensors were supplemented by using the radar in the Terrain Avoidance mode. In addition a low height warning triggered by the radar altimeter, as on production AM-X, was available.

As far as terrain avoidance is concerned, it became clear that together with the type and performance of sensors, an additional factor to be considered is the availability of a precise present position computation. In fact, when IN/GPS systems are available and extremely precise performances ensured, external world visibility requirements could be relaxed. In these cases availability of the FLIR alone could be sufficient, since navigation updating requires limited search of check points on the ground.

Although simulation fidelity as far as depth perception is limited (as discussed previously), some considerations could be derived by the tests performed when simulating availability of a fixed FLIR only. In these cases, maximum currently available HUD FOVs (in the order of 20 deg vertically by 30 deg horizontally) should restrict manoeuvring on a flat terrain to approximately 60 deg turns. This limitation should go down to about 45 deg turns on a hilly terrain: however, these considerations will require to be confirmed with appropriate in-flight evaluations, specially to quantify limitations on a mountainous terrain.

In addition, with such a configuration the impossibility to have a "look in the turn" capability should restrict the capability of manoeuvring when under radar or missile threat, so it should be necessary to reduce the height down to 200 ft and to make extensive use of terrain masking together with use of electronic counter measures and chaff/flares.

In case of degradation of the IN/GPS system, the necessity of using NVGs for searching the fix point should arise. However continuous use of NVG during navigation increases physical workload; furthermore, when NVGs are used, there a danger of disorientation when continuously transitioning from looking to the external world to inside the cockpit.

Use of a radar in a terrain avoidance mode is of course an improvement, but its necessity has been questioned. In fact in a single-seat version the pilot's workload in flying the aircraft at low height on a mountainous terrain using terrain masking and counteracting enemy threats has

been considered so high that even a limited part of his attention could not be dedicated to use the radar MFD. Of course, being the task of managing ground mapping modes even more demanding, it was immediately verified the unacceptability of such a task.

On the contrary, in a twin-seater the N/WSO could effectively use the radar in all A/G modes for checking ground clearance during the route and maintaining position confidence.

In all cases availability of a geographic map with easy to understand navigation symbology has been considered essential. Also availability of a Flight Director system has proved to increase mission effectiveness helping the pilot to follow the planned route/timing more precisely: in addition when the Flight Director has been used, pilot's attention was more effectively dedicated to perform the low height flight and managing nav/attack and self defense sensors. To this extent, also an autothrottle facility has been considered an useful, desirable improvement.

Another outcome of this analysis has been the requirement for a Ground Proximity Warning System (GPWS) to increase the now available simple radar altimeter low height warning: in fact simulation tests confirmed that to ensure safe ground separation when looking inside the cockpit the pilot inevitably increases height. A GPWS, using some sort of forward looking sensor like a laser ranging equipment, should be able to alert the pilot of the presence of obstacles in front of the aircraft increasing pilot confidence when flying at very low heights.

Navigation Precision

Performances made possible by use of the Litton LN39 Inertial Navigation system currently available on the AM-X have been considered adequate for most of the night-attack CAS mission requirements.

On the other hand, more prolonged BAI mission profiles should require performance of a number of navigation fixing procedures. In this case availability of a N/WSO is considered a great relief for the pilot's workload. In fact simulation tests confirmed that in a twin-seater availability of the N/WSO should reduce pilot's workload particularly in preparing for navigation updating procedures and should assist in searching and detecting the fixing point, specially on off-track points.

However, availability of GPS in the precision mode could further increase navigation precision, reducing the need of performing navigation fixing procedures and thus rendering more acceptable also a single-seat configuration.

Target Search, Detection and Identification

In CAS missions it is essential to search, detect and identify ground targets prior to commit weapon release.

This activity is done while manoeuvering the aircraft so the field of regard should be as large as possible.

Fixed FLIR FOV has demonstrated to be inadequate for such a requirement. If FLIR is to be used, this should be slewable with image presentation on an Helmet Mounted Display (HMD).

However, up to now adoption of a slewable FLIR integrated with a HMD has been demonstrated to be a complex (and costly) option. If these disadvantages could not be overcome in the next future, use of NVGs could be considered adequate if used for not extended periods.

The utility of using a multi-mode radar in a ground mapping mode for target detection and designation when flying at low heights is a controverse issue, that should require additional test activities. However, tests performed so far resulted in a number of considerations:

- although the radar simulation available so far was not intended to simulate a specific equipment, it included emulation of typical capabilities of radar equipment generally used in this class of aircraft.
  The performed evaluations demonstrated that interpretation of radar returns for target search and identification was affected by the capabilities available with the basic ground mapping modes, particularly on the single-seat version where the pilot workload in the attack phases was quite high.
  In fact, it has been verified that sharing the pilot's attention in the attack phase between the task of flying at low level at night while counteracting enemy threats and at the same time detecting, identifying and selecting the target is unacceptable.
  For this reason, to enable effective use of ground mapping radar on the single-seater, it is expected to provide high integration of radar with other sensors (e.g. targeting pod, navigation system to overlay on the radar format IN/GPS derived navigation data plus geographic map) and developing very high level of automation of selected functions and information presentation;

- alternatively, the increase of the available amount of resources obtained by the presence of a N/WSO on a two-seat version made the ground mapping mode useful.
  In fact, in this case all radar correlated tasks are effectively performed by the

N/WSO leaving to the pilot the task of conducting the flight and counteract threats, so a less sophisticated radar and integration level is considered adequate.

Data Entry Facility
Current AM-X use a head-up Navigation Data Entry facility to enter navigation and target data during flight.

Simulation of night operations in a single-seater demonstrated the necessity to extend head-up data entry to comms frequency/channels, IFF codes, data-link messages etc. This has become more evident when using NVGs.

However, a well designed comprehensive head-up data entry facility is required also in the rear cockpit of a twin-seater. In any case the presence on-board of a N/WSO has been considering of high relief as far as navigation, comms and IFF systems moding is concerned.

In addition, availability of a data-link is considered a firm requirement for the single-seater, in order to alleviate the necessity of entering data, specially in CAS missions.

Targeting Pod Operation
Use of a targeting pod with laser ranging / illumination capability has been confirmed to be important.

However, this simulation activity has not been dedicated to evaluation of performances increase made possible by using or not the targeting pod. Major aim of this activity has been the evaluation of pilot's procedures and comparison on a single- and two-seater.

These resulted in the verification that use of a targeting pod flying at low height at night on a single-seater is extremely difficult. In fact, as far as CAS missions are concerned, the extremely limited time available on the target area to detect targets reduces its potentialities. In this case, in order to be helpful, the targeting pod mechanization should be highly automated reducing to a minimum the pilot's intervention.

Slightly different is the case of BAI missions, where it should be possible for the pilot to perform off-set point designation in a relatively calmer attitude. Also in this case automation is a requirement for keeping the target illuminated after weapon release when leaving the target area avoiding enemy defenses.

In all cases the utility of integration of radar and targeting pod aiming symbology on HUD has been confirmed.

Situational Awareness
The information available on the Situation Awareness MFD has been positively considered. However some comments have been collected, in particular regarding the necessity of a careful design of the Situation Awareness display formats since its use in low height missions at night requires an easy to understand, not cluttering presentation of information.

In addition it is required to present threats information also when flying head-up (e.g. appropriate symbology on the HUD and/or voice messages).

The possibility of having a system capable of suggesting escape manoeuvres in case of detection of threats has also been considered a requirement. This information should be presented on HUD (or HMD).

Availability of a data-link has been considered very usefull to present real-time threat updating during the mission.

Another suggestion has been the presentation on the geographic map of enemy radar coverage, including terrain masking features at different altitudes.

DESIGN SUGGESTIONS

From the above discussed results of the simulation tests some design suggestions can be derived that should be considered when deriving a night/marginal weather attack version of the AM-X.

A first general consideration can be made about the basic respondance of the AM-X configuration to the specific requirements of a night-attack version. This means that the air vehicle configuration can basically remain unaffected by this evolution.

The avionic system, and in particular the navigation and attack sub-systems together with displays and controls, is the most affected by the configuration changes necessary to satisfy the considered requirements.

The perhaps major question, i.e. the single- versus twin-seat configuration, has not been completely solved, but initial results show that a decision in favour of either configuration severely influences the performance and integration levels of the navigation and attack sensors.

With data collected so far a number of configuration options has been derived. These are summarized in Table I and compared with the current basic AM-X configuration. However, it must be clear that further activity is still necessary to confirm these preliminary results as well as better detailing design requirements.

All suggested nav/attack sensor configuration options have been considered for both single-

and twin-seat aircraft configurations. In the following they are briefly discussed.

Option 1: Improved
This option is derived by the current day-attack AM-X mainly with modification of the nav/attack sensor suite. This, as illustrated in Table I, includes installation of a fixed navigation FLIR with associated wide-angle FOV HUD, use of NVGs, replacing the current ranging radar with a multi-mode radar, adding a targeting pod to be used as an alternative to radar for ranging purposes and for laser target designation, and adopting a map generator.

This configuration in the single-seat version is considered poor as far as mission effectiveness is concerned since, as derived by evaluation carried out so far, the operational advantages that could theoretically be made possible by addition of multi-mode radar and targeting pod are vanified by the pilot's workload increase, particularly in the ingress/egress and attack phases.

Missions effectiveness should be higher when considering a twin-seat configuration, due to the availability of the N/WSO that can relief the pilot in most critical navigation and attack tasks.

Option 2: Advanced
This option (see Table I) is derived by Option 1 with addition of GPS integrated with INS, a GPWS and a data link system as well as improving the man-machine interface.

With these improvements it is considered that mission effectiveness can be adequate with a single-seat configuration for both CAS and BAI missions only if operating in some less demanding scenarios, like for example on flat terrain, at relatively higher navigation and attack heights or low threat levels. In fact the added systems can help the pilot in some workload intensive tasks but workload levels remain high.

Additionally, for the CAS mission, the availability of the ground mapping radar resulted useless since, due to the high workload as already discussed for Option 1, the pilot is still not in the condition of taking advantage from it.

On the contrary, presence of the N/WSO on the twin-seater version is considered capable of enabling higher mission effectiveness.

Option 3: High Integration
This configuration, that is only a conceptual one since it has been neither tested on the Flight Simulator nor defined analytically, is supposed to incorporate higher integration and automation levels than the other ones, assuming this can be made possible in the medium term by technological progress specially in the field of man-machine interface and Advanced Information Processing.

Use of an advanced radar with intelligent automated modes could be useful, but its necessity could be questioned if an automated intelligent IR/laser targeting capability is available.

Based on this assumption, it is foreseen that also a single-seater configuration could allow high operational effectiveness retaining acceptable pilot's workload, but this needs to be confirmed by specific studies. Also cost-effectiveness should thoroughly be evaluated.

CONCLUSIONS

Even if in a very preliminary form, evaluations performed on the Alenia AM-X Flight Simulator have enabled to highlight a number of possible requirements that should be taken into consideration when developing a night/marginal weather attack version of the AM-X aircraft.

Data collected so far seem to confirm the results of the pre-feasibility studies performed in the past, that suggested that higher operational effectiveness levels should be achieved with adoption of a number of improvement to the actual AM-X navigation and attack sensor configuration, including addition of a GPS, Navigation FLIR, NVGs, multi-mode radar and targeting laser pod on a twin-seater platform. Alternatively, similar results should be achieved with a single-seater configuration if high sensor integration and automation levels can be provided.

However, a number of alternative aircraft and nav/attack sensors configuration options with intermediate levels of sensor integration and automation have been considered, but preliminary results tend to indicate higher degrees of pilot's workload and lower mission effectiveness levels when a single-seater configuration is retained.

These results are not conclusive, since additional evaluations are still necessary to better define these options and to assess in detail mission effectiveness levels for each configuration option.

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LIST OF ABBREVIATIONS

AAA	Anti Aircraft Artillery
A/A	Air-to-Air
A/S	Air-to-Surface
BAI	Battlefield Air Interdiction
CAS	Close Air Support
CCRP	Continuously Computed Release Point
CGI	Computer Generated Imagery
CM	Contour Mapping
CP	Control Panel
D/A	Digital/Analogue
FAC	Forward Air Controller
FEBA	Forward Edge of Battle Area
FLIR	Forward Looking Infra Red
FMP	Flight Mechanics Panel
FOV	Field Of View
GM	Ground Mapping
GPS	Global Position System
GPWS	Ground Proximity Warning System
HOTAS	Hands On Throttle And Stick
HMD	Helmet Mounted Display
HUD	Head Up Display
IFF	Identification Friend or Foe
INS	Inertial Navigation System
IR	Infra Red
LGB	Laser Guided Bomb
MFD	Multi-Function Display
NVG	Night Vision Goggles
N/WSO	Navigator/Weapon System Officer
SAM	Surface to Air Missile
S/A	Surface-to-Air
TA	Terrain Avoidance
TOO	Target Of Opportunity
VFR	Visual Flying Rules
WG	Working Group

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The authors like to express their thanks to the team at the Flight Simulation Center at Alenia Aeronautica in Torino which contribution has been essential for the conduction of the described activities.

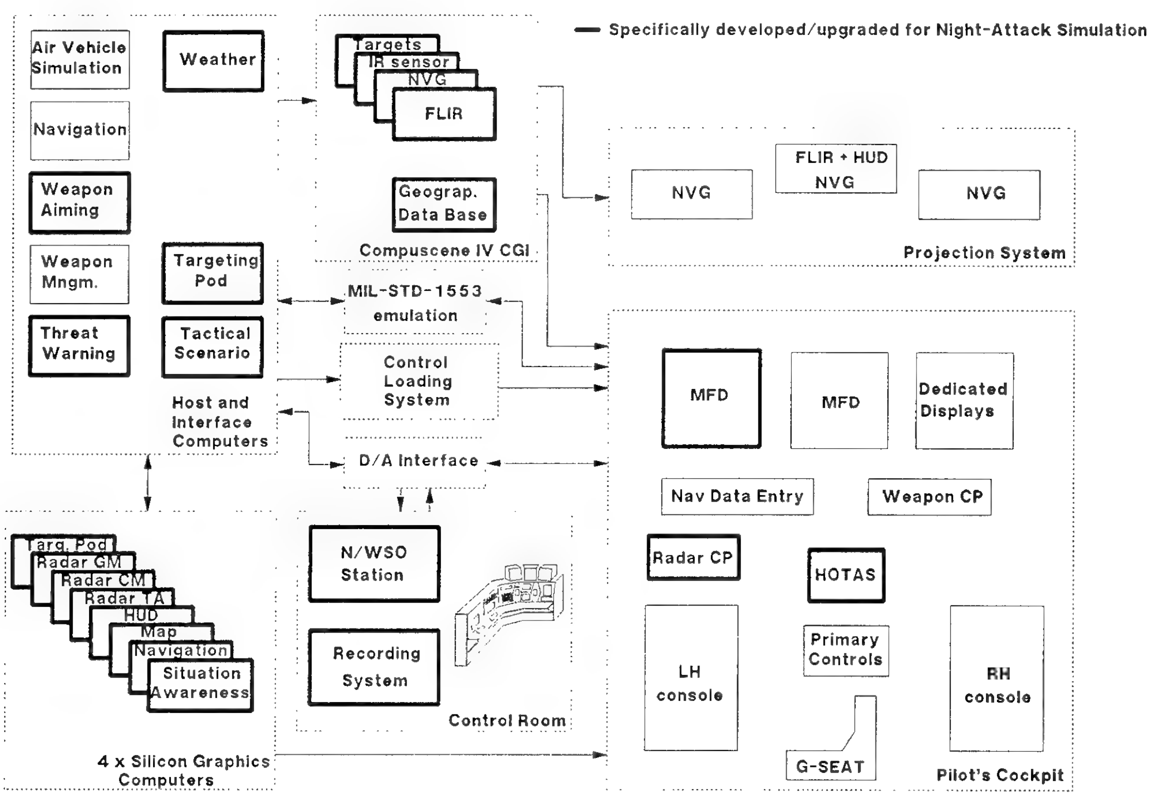


Fig. 1

Variant	Configuration	Low Height Night/Marginal Weather Mission Effectiveness			
		Single-seater		Twin-seater	
		CAS	BAI	CAS	BAI
0 - Basic	- Stroke HUD - Ranging Radar (FIAR Pointer) - INS - Flight Director - 1 raster/stroke colour MFD - Head-up Navigation Data Entry	Day only	Day only	as single-seater	as single-seater
1 - Improved	- **Fixed navigation FLIR + NVG** - **Raster/stroke wide-angle FOV HUD** - INS - Flight Director - Head-up Navigation Data Entry - **Map generator** - **2 raster/stroke colour MFDs** - **Multi-mode radar with GM/TA/CM modes** - **Targeting pod**	poor	poor	adequate	adequate
2 - Advanced	- Fixed navigation FLIR + NVG - Raster/stroke wide-angle FOV HUD - Multi-mode radar with GM/TA/CM modes - Targeting pod - INS**/GPS** - Flight Director - Map Generator - 2 raster/stroke colour MFD **- Head-up Nav/Comms/IFF Data Entry** **- GPWS** **- Data Link**	adequate (redundant)	adequate only in particular scenarios	high	high
3 - High Integration	**- Slewable navigation FLIR + HMD** **- Advanced radar with intelligent automation (necessity to be demonstrated)** **- Targeting pod with intelligent automation** - INS/GPS - Data Link - Flight Director/**Attack Autopilot** - Map Generator **- State-of-the-art displays and controls with Crew Assistant option** - GPWS	high (?)	high (?)	n.a.	n.a.

Table I

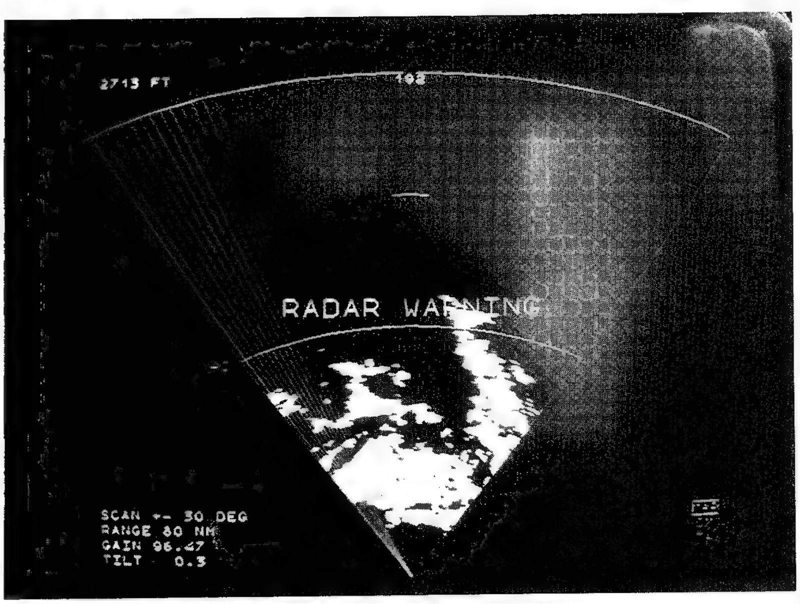


Fig. 2

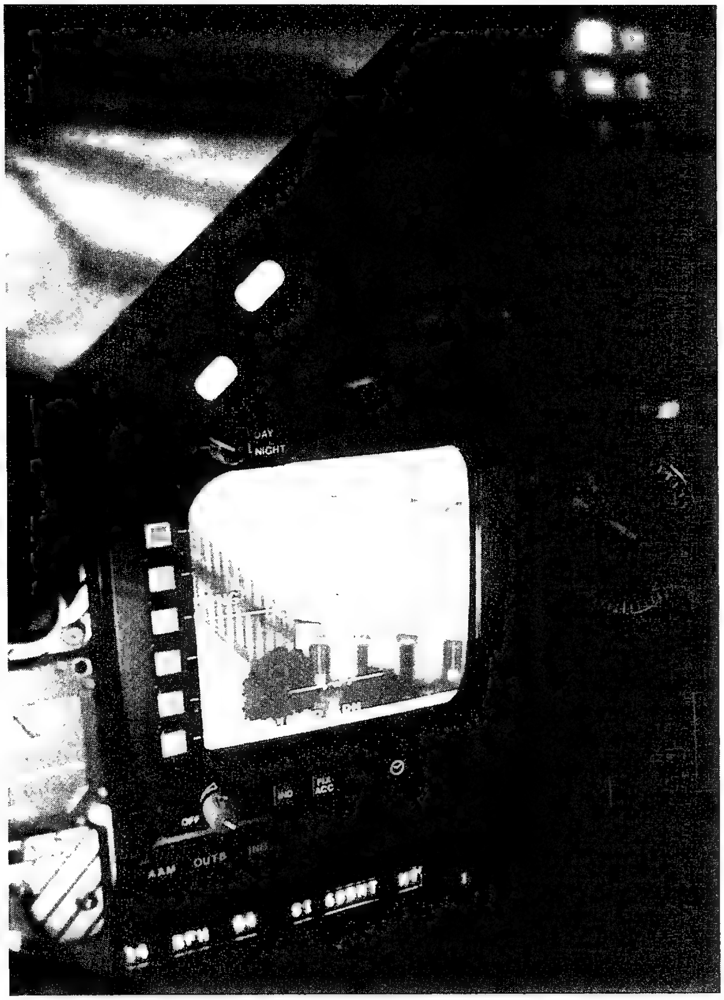
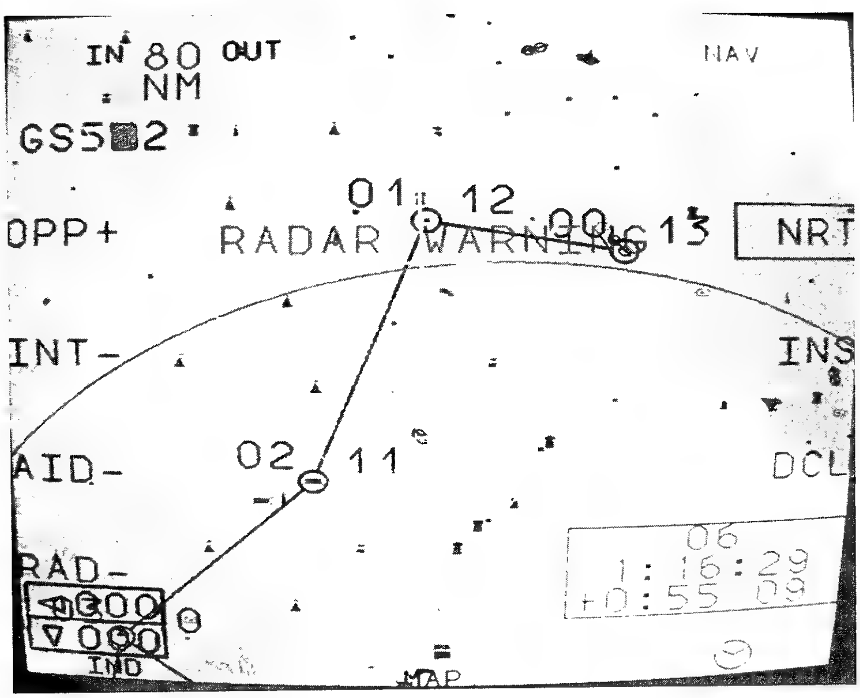


Fig. 3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NM
NAV
GS5■2
01 12
OPP+
RADAR
13
NRT
INT-
INS
AID-
02 11
DCL
RAD-
06
1:16:29
+0:55 09
IND
MAP

Fig. 4

UN VISUEL DE CASQUE POUR LA MISSION DE NUIT A BASSE ALTITUDE

Jean-Pierre Cursolle, Alain Leger, Franck Leppert
SEXTANT Avionique
BP 91 Rue Toussaint Catros - 33166, Saint Medard en Jalles cedex
France

1. ABSTRACT

The achievement of air to ground mission in a complex operational context, with bad meteorological conditions and, moreover by night is a very demanding task for the pilot . This mission requests a high situation awareness which can be only reached with specific, accurate and reliable means, such as sensors, displays or controls, perfectly integrated in the aircraft system .

The mission can be successfully realized thanks to sensors performances. But, the use of FLIR or I^2T depends on a lot of conditions such as weather with bad effects on the efficiency . So images must be enhanced with symbols to be fully exploitable. Futhermore, the sensors has to be fully integrated, the efficiency depending on the interfaces such as displays and controls . The third Generation Helmet Mounted Display is an answer to this requirement but has to be fighter pilots customized .

The conference will include a few operational requirements recall, the Sextant Gen 3 HMD description and will highlight the first symbology results issued from a ground simulation assessment.

2. INTRODUCTION

La capacité d'un avion de chasse moderne est liée au type de capteurs embarqués, à l'armement associé et à l'efficacité du couple pilote/système. Cette efficacité est totalement dépendante de l'interface choisie et du type d'informations présentées.

Les techniques optiques et électroniques les plus récentes sont utilisées pour mettre à la disposition des pilotes de combat des visualisations collimatées à grand champ comme par exemple la Viseur Tête Haute (VTH) du Rafale qui offre un champ de 30° x 22°. Les informations opérationnelles issues des senseurs embarqués sont ainsi introduites très tôt dans le champ visuel du pilote et l'importance du champ optique donne un excellent moyen de présenter des informations d'orientation spatiale en superposition avec le monde extérieur.

De la même façon, dans sa fonction Vidéo, la VTH permet de collimater à l'infini une image issue d'un Flir. Cette visualisation améliore considérablement l'efficacité des avions de combat lors de missions de pénétration. L'image présentée reste toutefois celle d'un objectif situé sur l'axe d'évolution de l'avion et ne donne pas au pilote toutes les informations nécessaires à sa sécurité lors de ses évolutions.

Pour étendre le domaine d'appréhension de la menace, qu'elle soit évolutive comme la menace aérienne ou fixe, comme les obstacles au sol, les spécialistes de l'interface Homme/Système dont nous faisons parti, ont développé une nouvelle interface, le Visuel de Casque (VdC).

Bien que ce sujet ait déjà fait l'objet d'expérimentation très sérieuses comme Falcon Eye, le sujet est suffisamment prometteur mais complexe pour nécessiter de longs et coûteux développements auxquels nous participons.

Nous approfondirons plus particulièrement l'aspect de la symbologie comme moyen d'appréhension de la situation de l'aéronef dans l'espace voire de pilotage en faisant état de campagnes d'expérimentation réalisées en simulation.

Paper presented at the Mission Systems Panel Symposium on "Low-Level and Nap-of-the Earth (N.O.E.) Night Operations" held in Pratica di Mare (Roma), Italy, 25-27 October 1994.

3. RAPPEL DES BESOINS OPERATIONNELS

Une analyse complète du besoin opérationnel est la base de toutes études et travaux sur le visuel de casque. Ainsi deux domaines différents émergent du besoin exprimé par les opérationnels.Le premier concerne le combat aérien et les actions d'autodéfense, et le second les missions d'appui et de pénétration.

3.1. MISSIONS DE DEFENSE AERIENNE

Précisons tout d'abord que le domaine d'emploi de VDC est limité au domaine d'engagement visuel qui est de l'ordre de 12 à 15 Nm. Il est, semble-t-il, inutile de présenter des informations dans le champ visuel du pilote à tout moment car ceci est source de fatigue et n'apporte aucune aide dans la manoeuvre offensive. Il n'en est cependant pas de même lors de détection de menaces car alors le pilote demande à être informé le plus rapidement possible. La présentation de l'information de position sera alors fournie instantanément.

En mission de défense aérienne, le VDC doit apporter au pilote plusieurs types d'informations. En premier lieu et de façon prioritaire, le VDC doit fournir au pilote tous les paramètres indispensables à la localisation des buts détectés par les capteurs de bord de types Radar, détecteur de menaces infrarouge et électromagnétique. En second lieu, le VDC doit présenter au pilote des informations sur son système d'arme du type sélection des missiles, affichage des domaines de tirs, mode des capteurs sélectionnés et des alarmes visuelles pour l'informer sur l'apparition de panne de son système dans des phases critiques de combat.

Enfin, et ceci fait l'objet de cet article , en phase de combat rapproché le VDC doit présenter une information sur l'orientation spatiale de l'avion principalement lorsque l'horizon n'est pas visible ou lors de phases de combat dans des couches nuageuses diffuses. Ces phases délicates de combat sont aujourd'hui très limitées malgré la sophistication des systèmes d'arme. Elles sont d'autant plus limitées que sous forts facteurs de charge, le pilote a de grandes difficultés à bouger la tête et ne peut plus venir chercher son information d'attitude dans le Head Up Display.

En phase d'autodéfense, le VDC doit permettre au pilote de rallier les capteurs de l'avion à la demande. Dans cette phase, le VDC donne au pilote les moyens de rallier instantanément ses missiles de combat et éventuellement de les tirer sans abandonner sa mission.

3.2. MISSION D'APPUI ET DE PENETRATION

Le vol et la navigation en basse et très basse altitudes sont facilités lorsque le pilote a une perception parfaite de l'environnement extérieur. D'une part, son orientation spatiale est grandement facilitée lorsque l'horizon est bien défini et le relief visible, et d'autre part, ses évolutions au sein du relief sont garanties s'il détecte les obstacles, perçoit les hauteurs et les vitesses relatives.

La réalisation de missions opérationnelles nécessite d'acquérir le visuel le plus tôt possible de points particuliers tels que obstacles artificiels ou repères naturels pour le recalage des systèmes de navigation et l'attaque d'objectifs militaires ou simplement le visuel des pistes et des installations aéroportuaires.

Ainsi, les images présentées dans le champ visuel du pilote au travers du VDC doivent lui donner la représentation du monde extérieur la plus fidèle possible, que l'on enrichira de symboles pour lui garantir son orientation spatiale et sa sécurité. L'image présentées devra se superposer le mieux possible au monde réel car un recouvrement imprécis ne pourra avoir qu'un effet négatif sur la confiance des pilotes envers le système.

Dans le cadre de ces missions, le pilote doit toujours avoir la possibilité de désigner des objectifs mobiles ou statiques et, inversement, le système doit pouvoir rallier les yeux du pilote sur la menace détectée par les capteurs.

Enfin, l'aspect ergonomique devient particulièrement décisif sur les avions de combat dans lesquels les équipages sont soumis à des facteurs de charge très importants et sont confrontés à des problèmes d'encombrement dans le poste de pilotage. Cet aspect est vital pour le pilote de combat qui va porter ce casque pour des missions de plus en plus longues avec des risques d'incident pouvant aller jusqu'à l'éjection.

3.3. QUELQUES CHIFFRES

En matière de contrôle du vol et de la navigation, deux aspects doivent être considérés. La perception du paysage qui va être survolé à court et moyen terme doit être aussi détaillée que possible pour permettre une identification rapide. La distance de perception doit être suffisamment grande pour optimiser le suivi du terrain ou le pilotage de l'appareil lors de missions d'appui sol et l'évitement des obstacles sans engager la sécurité. La perception du monde latéral doit également être assurée afin de préserver la sécurité et faciliter l'orientation spatiale.

L'expérience montre qu'un préavis de 15 à 20 secondes de vol est suffisant pour assurer un pilotage à vue. La distance reste bien sur dépendante de la vitesse de l'avion mais le minimum requis peut être défini comme étant la distance minimum qui offre le préavis nécessaire pour effectuer une manoeuvre coordonnée et sécurisée.

La détection d'obstacles tels que pylônes de lignes à haute tension ou antennes de 3 mètres d'épaisseur et de 60 mètres de hauteur doit être réalisée entre 1,5 et 2,5 km.

Pour les recalages de navigation ou l'attaque d'objectifs militaires, la détection et la reconnaissance de points géographiques de taille typique 10 x 5 m doit être réalisée à une distance de 3 km.

Enfin, l'anti-collision face à la menace aérienne doit être assurée en toutes circonstances.

4. UN VISUEL DE CASQUE POUR LA MISSION AIR/AIR

Pour la mission de Défense Aérienne, le VDC doit avant toute chose ne pas entraver les mouvements de tête du pilote dans la cabine. Le casque Topsight (annexe 1)répond à cette contrainte en proposant un encombrement minimum, une masse de 1,45 kg et un centrage particulièrement optimisé.

Le dispositif optique permet la présentation d'un champ de 20° en projection sur la visière avec une collimation à l'infini. L'image est produite par un tube électronique de 1/2 pouce. Les calculs de détection de position, la génération de symboles et le pilotage du tube sont réalisés dans un boîtier de soute. La présentation de l'image s'effectue en mode cavalier ce qui permet de disposer d'une excellente dynamique de brillance et contraste en toutes circonstances d'emploi.

En utilisation opérationnelle, le système propose un couplage au Radar, aux missiles de combat, à la centrale à Inertie et, si la précision est suffisante, aux détecteurs d'alerte infrarouge et électromagnétique.

D'autre part, le système propose un ensemble d'informations sur la conduite de l'avion, la surveillance des systèmes et la gestion de l'armement que le pilote peut ou non sélectionner.

L'exploitation de toutes ces informations s'effectue au travers de la symbologie.

5. UN VISUEL DE CASQUE POUR LA MISSION AIR/SOL

L'ergonomie reste bien sur un critère déterminant pour l'équipement des pilotes de combat.

Le casque Topnight (annexe 1) regroupe toutes les fonctions de protection physiologique dans un casque de type "intégral" dont la masse n'excède pas 1,850 kg et au centrage particulièrement optimisé.

Les images sont produites en mode cavalier pour toute la symbologie et en multimode lors de la présentation d'image vidéo. Elles sont collimatées à l'infini par un dispositif optique binoculaire de 40° x 30° à projection sur visière. Elles sont générées par deux tubes électroniques de 1/2 pouce pilotés par un boîtier électronique de soute. La détection de position de la tête permet d'asservir la position des capteurs à la ligne de visée du pilote avec une précision de 0,25°.

En utilisation opérationnelle, le système présente au pilote les images de deux types de capteurs. Un IL CCD est intégré dans le casque et permet la réalisation de mission de nuit dans 60% des cas. Un Flir orientable produit une image autorisant également les missions dans 60% des cas. La complémentarité des deux systèmes, sélectionnés selon les conditions météorologiques, amène une disponibilité opérationnelle de l'ordre de 80%.

Cependant bien que présentée dans un champ de 40° x 30°, l'image peut par moment s'avérer insuffisante en taille et en qualité. Aussi est-il nécessaire de venir l'enrichir. Cet enrichissement reste très classique puisqu'il se fait à l'aide de la symbologie dont la teneur sera abordée dans le chapitre suivant.

Parallèlement, le pilote dispose pour assurer sa mission de toutes les données nécessaires fournies par son système d'arme sous forme de symboles. Toute détection de menaces par les capteurs de bord lui est automatiquement présentée. Le Visuel de Casque dans sa fonction désignation lui permet également d'accrocher les missiles sur tout hostile qu'il identifierait sans se démasquer.

6. LES ESSAIS DE SYMBOLOGIE

6.1. INTRODUCTION

Le Visuel de Casque pour le vol basse altitude dans un avion d'arme n'a encore jamais été utilisé en France. Aussi, les essais devant débuter très prochainement, il a été décidé d'effectuer une évaluation du besoin de symbologie et tenter de figer une première définition de celle-ci.

Au delà de la mise au point d'une symbologie "d'orientation spatiale" destinée aux essais en vol, le but de l'expérimentation a consisté dans un premier temps en une évaluation comparative de deux concepts de symbologie, la symbologie dite "synthétique" et la symbologie dite "conforme" (annexe 2).

Une seconde phase expérimentale a été ensuite consacrée au développement du jeu de symbologie de base, en tenant compte des résultats obtenus précédemment.

6.2. ENVIRONNEMENT MATERIEL ET LOGICIEL

Il est commun aux deux phases expérimentales. Le dispositif s'articule autour d'une station de travail Silicon Graphics "ONYX" et du casque Topnight .

Les images générées en mode vidéo sont asservies au mouvement de la tête, le pilote étant par ailleurs en contrôle des évolutions du modèle avion de simulation. Elles sont présentées en monochrome vert, dans un champ de 40°x30°. La qualité des images a été jugée meilleure que ce qui est actuellement généré par les capteurs réels (caméra thermique ou JVN), mais l'ensemble de la simulation a été globalement jugé comme suffisamment représentatif et acceptable pour les objectifs poursuivis.

Les pilotes étaient installés dans une cabine de Mirage 2000 sur un siège MK 10. Les manettes de contrôle (manche et gaz) étaient simplifiées et non représentatives des dispositifs réels.

La cabine ne comportant aucun instrument, les pilotes ont été placé dans une situation d'immersion virtuelle complète.Une visière totalement opaque était alors utilisée. Une symbologie classique HUD M 2000 apparaissait dans l'axe de la cabine et était remplacée par la symbologie périphérique lorsque la tête du pilote s'éloignait de l'axe du fuselage.

Au cours de la seconde phase expérimentale, cette situation d'immersion a été complétée par la réalisation d'une condition de semi-immersion.Dans ce cas, le pilote pouvait voir les structures de la cabine au travers de la visière, une toile noire opaque isolant la cabine dans le local d'expérimentation.

6.3. SCENARIOS OPERATIONNELS

Les scénarios opérationnels ont été définis par les conseillers pilotes de Sextant

Trois scénarios de base ont été retenus :

A : Pénétration Basse Altitude - attaque d'objectif - Sortie des lignes

B : A + passage IMC point clé haut.

C : Navigation en zone hostile avec menaces.

6.4. DEROULEMENT DE L'EXPERIMENTATION

6.4.1. Consignes préliminaires

La séance de travail était précédée d'un exposé aux pilotes du but de l'expérimentation et d'une présentation statique des différents éléments de symbologie.

Pour l'exécution des scénarios de mission, les pilotes étaient informés des priorités à respecter du mieux possible (altitudes et vitesses), mais avant tout la réalisation de la mission était recherchée, quelles que soient les conditions rencontrées (en particulier passages en IMC).

6.4.2. Entraînement

L'entraînement comportait 3 phases :

- Evolutions libres (comportant au moins un atterrissage). Il s'agissait d'une prise en main des contrôles et d'une accoutumance aux différentes caractéristiques de la simulation.
- Présentation en dynamique de la symbologie synthétique, évolutions libres (durée selon demande pilotes).
- Présentation en dynamique de la symbologie conforme, évolutions libres (durée selon demande pilotes).

A la fin de l'entraînement, le pilote avait une connaissance suffisante de l'environnement de simulation et il maîtrisait les caractéristiques de pilotabilité du simulateur, ainsi que la signification des différents symboles.

6.4.3. Plan d'expérience

<u>Première phase expérimentale</u>

Tous les scénarios étaient réalisés par chaque pilote, chaque pilote étant son propre témoin. Trois conditions de symbologie viseur de casque étaient utilisées pour chaque scénario, synthétique (SY), conforme (CF), pas de symbologie (N).

En tout, chaque pilote effectuait 9 essais résultants de la combinaison des 3 scénarios (A, B, C) avec les trois symbologies. L'ordre de présentation des combinaisons était réalisé selon un plan type "carré latin" pour éviter les effets d'ordre. Le tableau ci-dessous donne l'exemple de ce plan pour les trois premiers pilotes :

Ordre de passage	1	2	3	4	5	6	7	8	9
Pilote 1	A,SY	A,CF	A,N	B,CF	B,N	B,Sy	C,N	C,SY	C,CF
Pilote 2	B,N	B,SY	B,CF	C,SY	C,CF	C,N	A,CF	A,N	A,SY
Pilote 3	C,CF	C,N	C,SY	A,N	A,SY	A,CF	B,SY	B,CF	B,N

Deuxième phase expérimentale

La deuxième phase expérimentale a été réalisée selon un protocole allégé, le scénario C n'étant pas utilisé.

Cette phase a uniquement porté sur l'évaluation de différentes alternatives de la symbologie conforme, modifiée en fonction des besoins exprimés par les pilotes dans la première phase.
Les sources de variations portaient sur le graphisme de l'indicateur Pente/altitude et sur la présentation des informations d'altitude et de vitesse (cadrans ou alphanumériques).

6.5. DONNEES RECUEILLIES

6.5.1. Variables quantitatives

Profil de trajectoire en altitude, profil de vitesse

Taux maximum de virage aux points clés et lors des manoeuvres d'évitement.

6.5.2. Données qualitatives

Un questionnaire d'évaluation était présenté au pilote à l'issue de chaque passe d'évaluation.Le contenu du questionnaire avait été déterminé avec la participation des pilotes experts de SEXTANT. Chaque question était notée selon une échelle d'évaluation comportant 4 niveaux, inspirée de travaux menés au Centre d'Essais en Vol.

Afin de compléter ce questionnaire sur le plan de la "Situation Awareness", un pilote expert de SEXTANT réalisait systématiquement une évaluation de l'état de "conscience de la situation" du pilote expérimentateur, en particulier dans les phases comportant des évolutions rapides.

6.6. RESULTATS

Les résultats obtenus portent sur différents points : validité de la méthode, symbologie conforme/non conforme, symbologie de base.

6.6.1. Validité de la méthode

En dépit de la grande "rusticité" de l'environnent de simulation, les pilotes expérimentateurs ont dans l'ensemble jugé que la technique utilisée permettait d'atteindre les buts fixés (évaluation de concept). Les points faibles de la simulation (modèle avion, image capteur, traînage de la symbologie et qualité du graphisme) ont été reconnus, mais, dans le contexte fixé, sont apparus suffisamment acceptables pour permettre de travailler efficacement.

La grande flexibilité apportée par l'utilisation d'une station de travail couplée au viseur de casque a par ailleurs été appréciée, dans la mesure où elle permettait d'accéder presque "en temps réel" à la présentation de modifications demandées par le pilote.

La situation d'immersion totale, même si elle a été globalement bien acceptée, pose plus de problèmes. En effet, il apparaît que les informations proprioceptives au niveau du cou ne permettent que très imparfaitement la détermination de la position de la tête par rapport aux repères cabine. Cette caractéristique, accentuée sans doute par la dimension restreinte du champ de vision, introduit des interférences néfastes sur la tâche de pilotage, en particulier lorsqu'il devient nécessaire de revenir rapidement chercher les informations stabilisées du HUD ou dans l'évaluation de la distance angulaire entre le nez de l'avion et la direction de la visée en périphérie. Cette situation n'est bien sur pas représentative de la situation d'emploi prévue en vol, qui est beaucoup plus proche de la situation de semi-immersion réalisée lors de la deuxième phase expérimentale.

6.6.2. Comparaison symbologie conforme et non conforme

Alors que la symbologie non conforme avait pour base les réflexions menées dans le cadre de la mise au point d'une symbologie "air-air", la solution de symbologie conforme s'est inspirée des travaux menés par la DRA et présentés récemment par J. INESON. Le concept "Bird cage" a été utilisé avec la représentation d'un élément de structure appartenant à l'avion (aile virtuelle). L'objectif

recherché étant essentiellement une aide à la perception de l'attitude plus qu'au pilotage proprement dit, aucune indication d'altitude, de vitesse ou d'énergie n'était présentée dans ce dernier cas.

En dépit de son caractère novateur, très éloigné des concepts classiques, la symbologie du type "bird cage" n'a pas été rejetée d'emblée par les pilotes. Un potentiel certain a été reconnu à ce type de concept, même avec la relativement faible dimension du champ du viseur. Il est cependant apparu assez rapidement que la précision requise pour évoluer en basse altitude ne pouvait correctement être atteinte avec la simple notion d'attitude fournie par la "bird cage' et l'aile virtuelle. Des ambiguïtés dans l'indication de montée/descente ont également été relevées lorsque l'inclinaison était forte. Mais surtout, dés que les évolutions devenaient rapides, un aspect très désorientant de ce type de symbologie est apparu, lié au traînage et au défilement des lignes, amenant à la constatation que la situation devenait "pire que rien" alors qu'elle était plutôt jugée "mieux que rien" avec la symbologie synthétique.

La symbologie synthétique a attiré également des critiques relativement sévères, aussi bien sur le fond que sur la forme. En particulier, la rupture de logique de présentation des repères d'attitude et de pente entre le HUD et la symbologie périphérique a posé un problème à certains pilotes. A elle seule, cette critique n'apparaissait pas vraiment rédhibitoire, mais les défauts de forme existant dans le jeu initial de symbologie synthétique rendaient clairement cette figuration inacceptable pour les évolutions en très basse altitude. D'un coté, il est apparu que le champ de vision limité et la qualité relativement pauvre de l'image du paysage ne permettait pas non plus d'exploiter les potentialités offertes par le viseur de casque, à l'exception de la fonction désignation. Les principales remarques faites sur la symbologie synthétique étaient les suivante :

- Taille globalement trop réduite de la symbologie
- Manque de précision dans la détermination de la pente
- Manque d'information en altitude et vitesse
- Manque d'information sur la cadence des évolutions dans le plan horizontal.

A l'issue de la première phase expérimentale, il est donc apparu que l'existence d'une symbologie périphérique superposée à l'imagerie était bien nécessaire pour évoluer en très basse altitude et exploiter les possibilités du viseur de casque. La symbologie synthétique, bien que présentant quelques défauts inacceptables sur la forme, est apparue comme la plus susceptible de pouvoir conduire à court terme à la réalisation d'un jeu de symbologie utilisable pour des essais en vol.

6.6.3. Symbologie de base pour les essais en vol

Le développement du jeu de symbologie pour la réalisation des essais en vol a donc exclusivement consisté en l'amélioration du jeu initial de symbologie synthétique.

Il est assez intéressant de constater que les évolutions amenées à partir des critiques des pilotes expérimentateurs a conduit à réaliser une symbologie représentative de la notion "T-Basic". On peut ici se demander si ce résultat est lié à la culture des pilotes (instruits et entraînés sur cette notion de base), ou si en périphérie comme en axial, le concept du "T-Basic" est tellement robuste pour le contrôle du vol qu'il s'applique à toutes les situations.

Les éléments de validation effectués dans la seconde phase expérimentale indiquent assez clairement qu'un très bon contrôle des évolutions de l'appareil peut être obtenu lorsque le pilote utilise la symbologie périphérique. Cette symbologie permet ainsi d'utiliser au mieux les fonctions de désignation et de présentation d'imagerie fournies par le viseur de casque.

Deux problèmes persistent cependant, plus au niveau de l'emploi que de la qualité des informations de pilotage. Il devient en effet extrêmement facile et confortable de piloter l'appareil en regardant sur le côté, amenant parfois à oublier que les éléments de paysage qui sont vus ne sont pas ceux qui se trouvent sur la trajectoire de l'appareil. De plus, le pilotage à l'aide d'une symbologie au graphisme proche de celle de la VTH entraîne une action à la « tête » avant une action au « manche ». Cette dernière observation disparait avec l'entraînement. La stratégie d'utilisation du viseur de casque par le pilote doit donc être élaborée en fonction de ces problèmes. Le choix s'est donc tout naturellement porté sur une symbologie informative limitant les possibilités de pilotage. Le pilote est alerté des changements d'attitude incontrôlé de l'avion, particulièrement par mauvaises conditions météorologiques. Il peut ainsi revenir rapidement en VTH rétablir sa trajectoire. A terme, on pourra coupler une fonction d'évitement de terrain pour compléter la sécurité du vol.

7. CONCLUSION

La symbologie développée pour les essais en vol a pour ambition de permettre au pilote d'exploiter au mieux une imagerie de qualité moyenne, comme celle résultant de la source IL intégrée au casque. L'approche retenue avec l'utilisation d'une symbologie synthétique non conforme est essentiellement fondée sur la notion "d'évitement de problème". Des essais complémentaires dans un contexte de récupération d'attitude unusuelle devraient permettre de tester la validité et la robustesse de cette symbologie en cas de problème avéré. Dans ce type de situation, certains éléments recueillis pendant la première phase expérimentale semblent indiquer qu'une symbologie conforme peut se révèler intéressante. Il semble donc opportun, parallèlement au essais de la symbologie synthétique, de poursuivre des études sur les bénéfices qui pourraient être retirés d'une symbologie conforme. Le premier point à examiner dans ce domaine est sans doute l'amélioration du graphisme et la connaissance des conditions limites à respecter pour éviter d'induire une désorientation là où une meilleure conscience de la situation spatiale est recherchée.

Cette symbologie, prolongement naturelle de la symbologie utilisée dans un Head Up Display ne représente qu'une partie des solutions. L'image elle même peut contenir les attributs permettant une meilleure « situation awareness ». Cet enrichissement complémentaire, symbolique lui aussi, consiste à exploiter un fichier de terrain numérique pour rendre l'image plus riche. Cette solution représentera sans doute la solution la plus efficace, mais elle demande des moyens de calculs beaucoup plus importants, une connaissance parfaite du relief et donc l'élaboration d'une base de données numériques précises du sol non encore disponible à ce jour.

Remerciements

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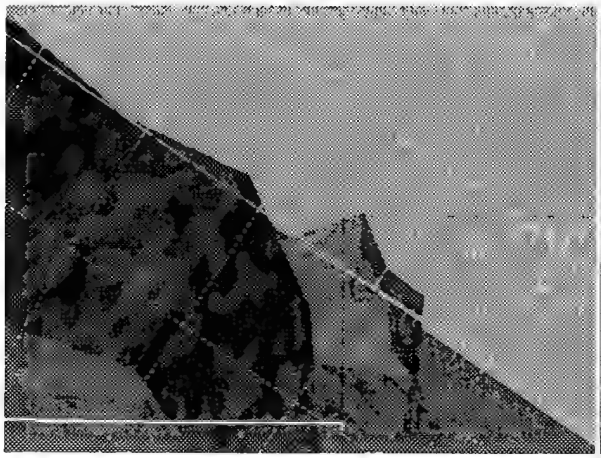
ANNEXE I

■ TOPSIGHT®

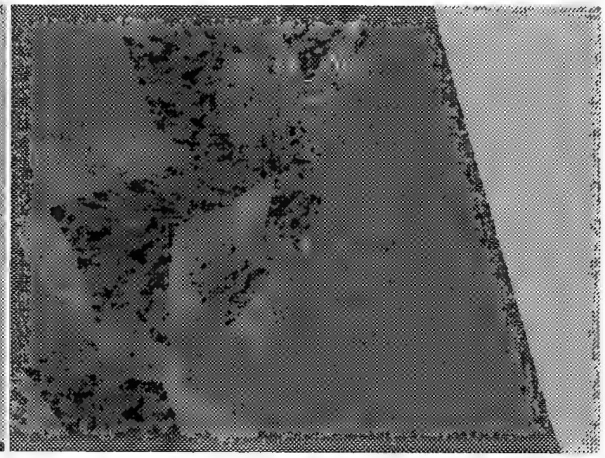
■ TOPNIGHT ®

SEXTANT AVIONIQUE

ANNEXE 2

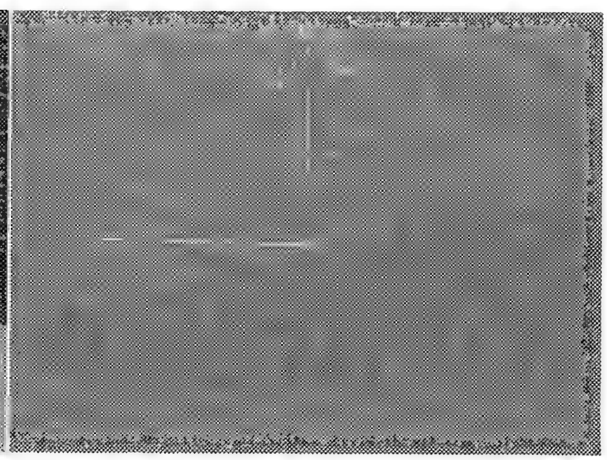


■ SYMBOLOGIE CONFORME



■ SYMBOLOGIE SYNTHETIQUE

■ SYMBOLOGIE d'ESSAIS VMC



■ SYMBOLOGIE d'ESSAIS IMC

SIRPH : Steerable InfraRed Picture On Helmet Mounted Display

Giorgio Balzarotti, Lorenzo Fiori, Beatrice Midollini
FIAR S.p.A.
Via G.B. Grassi, 93 -20157 Milano-Italia

ABSTRACT

Helmet Mounted Displays (HMDs) are being paid remarkable attention as an essential aid to pilots of both fixed and rotary wing aircraft: the technological improvements such equipment are experiencing place them in an outstanding position among avionics.

A very important role in the success of HMDs is played by the management of man-machine-interface aspects: the way how to make the information available, in a useful format, to the pilot must be considered with particular care. A smart example is the presentation of images from steerable sensors: the head tracking systems have actually achieved a high degree of accuracy, thus allowing a precise control of the Line Of Sight (LOS) of electrooptical vision systems. Therefore, pictures generated by a steerable infrared sensor slaved to the pilot's head movements can be displayed onto the helmet visor, in order to provide the pilot with a substantial aid in day and night, adverse weather conditions, high altitudes down to low level and nap of the earth flight operations.

The paper describes the results of a technical analysis performed on a system based on a steerable IR sensor integrated with an advanced HMD for navigation aid purposes.

The parameters which lead to an imperfect static or dynamic overlay of the generated IR picture with the external world, as seen by the pilot through the helmet visors, and the effects of such misalignment are analysed in details, together with integration aspects and human engineering factors.

The analysis has also taken into account the finite angular excursion of the IR sensor LOS, originated by gimbals limits, and the consequent necessary transition to and from the LLTVs integrated within the helmet, suitable to cover all possible head motions, has been investigated.

An approach to the problem of the fusion of information generated by the IR sensor and the LLTVs is also reported.

Finally, the paper highlights the limits and the constraints of navigation using a steerable IR sensor, with respect to safety aspects.

1. INTRODUCTION

The use of virtual image displays to present flight data to the pilot, so that they can be observed overlaid on the outside world focused at, or near, infinity is nowadays of common use on board of aircraft. The Head Up Display (HUD) is the most common virtual image display to present symbols and, now, also images generated by vision sensors such as FLIRs. An accurate overlay of the FLIR picture with the outside world seen through the HUD combiner allows to have a powerful and safe aid to the navigation with workload reduction beneficial to the pilot.

The strongest limitation of HUD is however its limited field of view (FOV) and its fixed LOS: displayed data and information are no longer visible as the pilot looks away from the combiner.

The recent development of accurate head trackers and of very light holographic combiners has allowed to extend the functions of Head Up Displays to Helmet Mounted Displays (HMDs), without limitation to the movements of the pilot's head.

2. GENERAL REQUIREMENTS FOR DISPLAYING IR PICTURES ON HMD

The most natural and attractive application of an IR sensor in the airborne environment is very likely the use by the pilot of the IR picture to fly and land. The characteristics of IR pictures are, in fact, such to provide great benefit particularly during night and in adverse weather conditions. Furthermore it is of absolute interest the capability to classify air or ground targets thanks to their pictures on the HMD, without looking to the head down display (HDD) at the cockpit, as this would force the pilot to distract his attention from the flight operations and, even, would require a stressing visual accommodation (focusing).

Here below the basic requirements for an operational mode which uses the IR sensor/advanced HMD combined system to provide the pilot with assistance during flight and

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landing, are outlined. This operational mode has been called 'Steerable InfraRed Picture on Helmet', with the acronym SIRPH.

2.1. SIRPH mode basic requirements

In the SIRPH mode the IR sensor LOS shall be steerable over the IR sensor field of regard (FOR) and shall be slaved to the commands from the HMD head tracker. The generated IR picture will have an angle coverage (i.e. FOV) compatible with that of HMD. The generated image shall be exactly overlaid to the outside world, as seen through the HMD, and without any latency (i.e. providing a true real time operation). The image shall be suitably occulted when the HMD LOS enters the cockpit zone to allow the pilot to perform cockpit management tasks, or, when the HMD LOS exceeds the IR sensor FOR limits, to display the image produced by the LLTVs. Automatic hot spot detection can also be included with highlighting of detections.

The contrast of the IR picture shall be suitably controlled to provide the best image in any scenario condition and during the continuous movement of the HMD LOS.

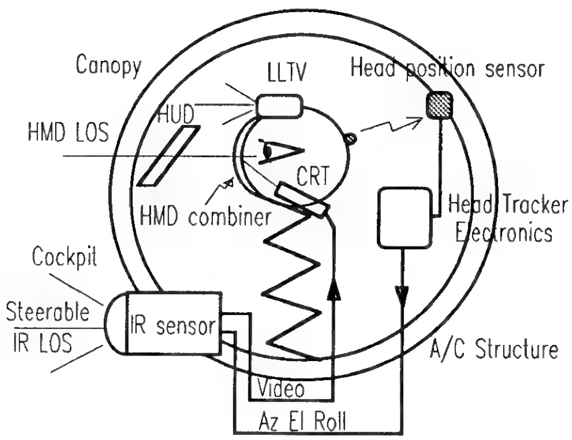

Figure 1. System pictorial diagram with highlights of main elements.

2.2 Classification mode basic requirements

Visual classification of targets using optronic sensors usually requires picture magnification (typically 3x or 4x). The picture shall be displayed on visor never causing confusion to the pilot.

3. SIRPH CONFIGURATION SCHEME

The technical analysis can now start, firstly introducing a simple sketch of the system in the SIRPH mode. Figure 1. schematically shows the architecture of the system, which includes the following basic elements: aircraft structure - canopy - cockpit - IR sensor - HMD with Head Tracker and LLTVs.

The IR sensor LOS is slaved to the HMD LOS in azimuth, elevation and roll, therefore to the pilot's LOS. Pilot's head movements are continuously tracked by the Head Tracker (including the Head Position Sensors) which, through a high speed digital link, provides commands to the IR sensor to steer its own LOS.

With such system the outside world is seen by the pilot directly through the optical combiners and the discrepancies between the IR picture and the outside world (i.e. overlay errors) are perceived in all the angular directions (azimuth, elevation and roll).

The contributions to the overlay errors come from:

- misalignment between the IR sensor and HMD LOSs
- geometric distortion and magnification differences

The above contributions are separately analysed here below.

4. IR SENSOR - HMD LOSs ALIGNMENT ERRORS

In the SIRPH mode it is essential that the errors between the IR sensor LOS and HMD LOS are kept to a minimum, as the IR image gives the pilot a feedback on the aircraft attitude. The effects of these errors are different, and have different importance depending on pilot's head movement conditions. In this document we have therefore classified the accuracies in tree categories:

- static accuracies
- quasi-static accuracies
- dynamic accuracies

'Static' and 'Dynamic' refer to the pilot's head movement condition.

The static condition is when the pilot's head is ideally fixed in a position.
The quasi-static condition is the realistic case of small and slow but continuous movements of the pilot's head.
The dynamic condition is when quick changes of pilot's head occur.

It is noted that all accuracies herein analysed are considered with respect to the nominal centre of the IR picture (i.e. the IR sensor LOS) and to the nominal centre of the HMD display (i.e. the HMD LOS) - see Figure 2. It is essential to have a perfect overlay at the centre of the displayed picture and, therefore, a correct control of the accuracies relevant to the two above LOS in that point is required. Discrepancies which lead to an overlay error off the LOS are considered however in Section 5.

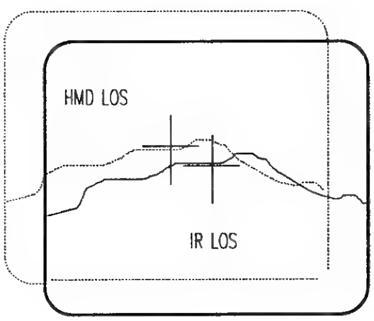

Figure 2. Pictorial view of overlay errors when IR sensor LOS is misaligned with respect to the HMD LOS

4.1 Static accuracies

In this case the accuracies are considered assuming that the HMD LOS is ideally fixed to a specific position within the IR sensor FOR. Although such condition does not operatively occur, it is essential to define the error breakdown which leads to the overall accuracies assessment as follows:

a) harmonisation and mounting errors.

This component takes into account the IR sensor mounting errors and the alignment accuracy achieved during the static harmonisation phase of the IR sensor with the HMD in the aircraft.

b) HMD harmonisation error Vs head motion box.

The static harmonisation of the HMD within the head motion box is generally performed for one or few reference points. The errors over the total head motion box (i.e. HMD angular and translation freedom) with respect to the harmonisation points are herein considered.

c) aircraft structural deformation

The IR sensor is hard mounted to the aircraft (A/C) structure and subject to external severe environment. The resulting A/C structural distortions which affect the LOS position are considered within c). The significant errors due to such A/C deformation during flight are taken into account and dynamically compensated by means of data stored in look-up tables and data provided by the A/C Inertial Navigation System (INS).

d) A/C canopy deformation

The pilot sees the outside world through the A/C canopy which introduces an angular error depending on the pilot's LOS position. As the IR sensor is obviously not affected by the canopy, the exact overlay of the IR picture with the external scenario can be achieved if the HMD provides the IR sensor with the so-called "true HMD angles" (i.e. the HMD LOS angles locally compensated with the relevant canopy correction data). As an alternative the correction could be also performed by suitably shifting the picture during presentation.

e) IR sensor LOS control

All the errors introduced by the steering control loop of the IR sensor are herein considered. This component concerns errors generated by angular sensors, non-linearity errors, analogue-to-digital transformation errors, data filtering etc.

f) translation error

This is a systematic error due to the different physical location of the IR sensor and the HMD in the A/C. The magnitude of the resulting angular error is inversely proportional to the range of the object/obstacle under observation. This error is however quite small in any practical operational condition.

g) IR Sensor - HMD communication delay

Delay from frame grabbing (IR sensor) to frame presentation (HMD) generates an error which is intrinsic of the imaging link IR

Sensor/HMD. The IR Sensor provides the HMD with the video signal not before 20 ms after frame grabbing, if an horizontal frame scan is implemented. Due to the aircraft motion such delay causes an overlay error. The overlay error is particularly evident in the elevation axis and can be successfully compensated by means of a suitable shift of the picture when the HMD LOS is close to the flight path direction (i.e. close to the stationary point for the displayed picture). When the HMD LOS is far from the flight path direction, the resulting effect is not limited to a shift of the picture in elevation, therefore it cannot be easily compensated. If a vertical frame scan is implemented, the delay is practically negligible as one line only instead of the full frame is grabbed.

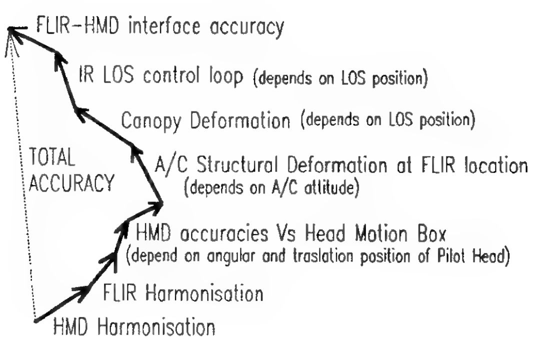

Figure 3. Graphic presentation of the HMD-IR Sensor LOS alignment error in the SIRPH mode. The total angle accuracies are the sum of many factors which are never constants.

The sum of the above accuracies, pictorially shown in Figure 3, is of the order of few milliradiants. The use of SIRPH requires an head tracker capable to guarantee accuracy of the same magnitude above, at least in the area close to the A/C boresight and within the most part of the head motion box.

4.2 Quasi-static accuracies

As already said, the quasi-static condition is the more realistic case when movements of the pilot's head are small and slow but continuous. Under these circumstances a good head tracking is required to provide the pilot with comfortable picture.
This condition has been modelled considering that the movements of the pilot's head are correlated in time: if the pilot's head is moving and accelerating, it is likely to suppose that direction and values will be the same after a quite small period of time. The 'correlation time' of such movements depends on the operational conditions: it is generally shorter when the pilot is visually tracking a target, it is longer when the pilot is surveying the scenario. The maximum acceleration of the head depends on the acceleration levels of the aircraft: higher acceleration levels compel the tendency/behaviour of the pilot to lock his head in a particular position and use his own eyes to track, if necessary [1].

Operatively, a continuous tracking of the HMD LOS is highly desirable to avoid lag effects or annoying step adjustment of the IR sensor LOS control loop, which leads to the impossibility for the pilot to correctly address his own sight.
Considering that the normal link rate is generally not higher than 50 Hz, the provision of the HMD angle rate in addition to the angular position is warmly recommended to optimise the tracking characteristics (bands and damping factors).

4.3 Dynamic accuracies

The perfect alignment of the IR sensor LOS and the HMD LOS during fast movements of the pilot's head is not operatively very important. Image motion - effective on the retina - due to head motions of 15 to 25 degrees/s may reduce visual acuity almost fivefold. Head turn rate of 100 degrees/s reduces the visual acuity to the level of blindness [2]. This means that high overlay accuracy is absolutely unnecessary for the implementation of a tracking loop capable to perform up to the maximum speed achievable by the pilot's head (greater than 100 degrees/s). Overlay accuracy requires tracking loop optimised to accurately perform with 50-70 degrees/s head turn rates, which are also compatible with the video frame reconstruction time (20 ms).

A short transient time is a more important parameter than the overlay accuracy, i.e. fast recovery without overshoots of the position after a quick head movement is strongly desirable. When flying with SIRPH a tracking loop transient time (i.e. from dynamic to quasi-static condition after a quick head movement) of about 1/3 -1/4 of the typical pilot's reaction time is necessary to be consistent with the dynamic of the movement of the head (see Figure 4).

The local control of the IR sensor LOS can be performed by means of a prediction filter which

processes only angular data of the HMD LOS, time tagged. In this case the use of angle rate data is beneficial to the tracking loop to overcome the problem of the finite update rate and the latency of the angle position.

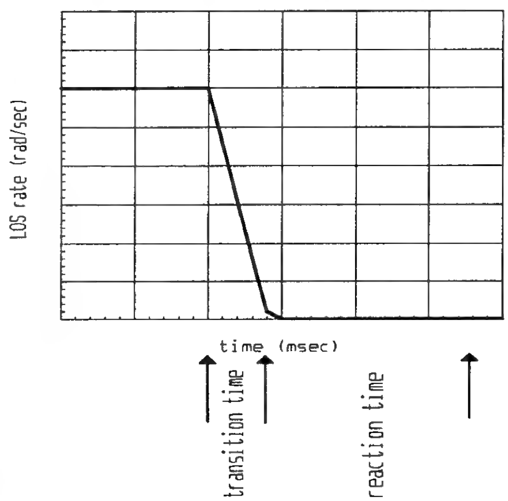

Figure 4. Transition time after a quick movement of the head should be short enough to be consistent with the pilot's typical reaction time for naked eyes operation.

5. OVERLAY ERROR OFF HMD LOS

The analysis provided in the previous sections was dedicated to the possible alignment errors between the IR sensor and HMD LOSs. A LOS error is primarily an overlay error resulting nearby the centre of the picture.
Off LOS there are additional sources of errors which affect the overlay accuracy of the whole picture with the external world (see Figure 5). To evaluate the overlay error off HMD LOS, the overlay error nearby the centre of the picture is assumed equal to zero.

Key sources for this additional overlay error are:

- IR sensor picture geometry distortion
- HMD picture geometry distortion
- A/C canopy distortion
- Magnification errors

An uncompensated geometry distortion of the IR sensor frame scanner, as well as of the HMD CRT and/or optics, can produce off-axis overlay errors. The effect of these distortions generally increases as the distance from the centre of the picture increases.

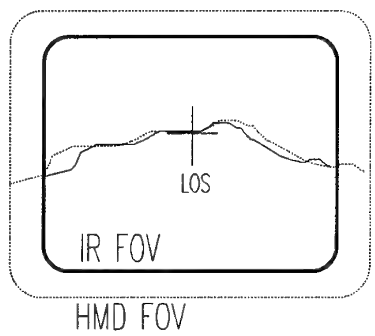

Figure 5. The elimination of the alignment error between the IR sensor and HMD LOS allows the achievement of a perfect overlay in the area nearby the picture centre. IR sensor and HMD intrinsic distortion, non linearity, A/C canopy distortion, magnification error cause a loss of overlay in the margin area of the FOV.

The A/C canopy introduces angular shift of the incoming optical rays. The amount of this shift depends on where the LOS intercepts the canopy itself. This effect has been already considered for the LOS, and the method for compensation already analysed; going to the edges of the picture on the HMD, however, an increasing residual distortion appears due to a different intercept of the sight with the canopy, thus decreasing the local overlay accuracy. The distortion is more evident with wide FOV - as in SIRPH - rather than with narrow ones. The compensation of this residual distortion, yet feasible in principle by local compensation on the picture using related canopy correction matrix, appears very difficult to be performed in real time for the whole picture. The overlay errors due to the A/C canopy are the most significant in the off-axis error budget.

Differences in the sizes not completely adjusted during the harmonisation of the picture generated by the IR sensor with the picture displayed on the HMD, appear as magnification error and also contribute as overlay error.

The objective difficulty in compensating the above errors does not constitute a limitation to the use of SIRPH, as a progressive degradation of the overlay accuracies from the centre of the picture to the edges can be reasonably accepted even under

an operational point of view (i.e. particularly at night or in adverse weather condition).

6. IR PICTURE REQUIREMENTS AND HUMAN FACTORS

6.1 Picture Stabilisation

Given the above consideration, a good alignment of the IR Sensor LOS with respect to the HMD LOS is achieved by suitably controlling the IR Sensor Steerer under the Head Tracker commands, but it cannot provide yet the pilot with a "stable picture" on the HMD: the picture is in fact subject to the A/C vibration. The effects of such vibration are not easy to be predicted: knowledge on A/C vibration spectrum is of paramount importance in the design of the interface to the pilot, but the behaviour of the human vision system can be fully verified under trials only. Recent tests on aircraft display readability under vibration[3] have revealed different human responses under specific trial conditions.

The operational time of SIRPH is entirely devoted to observation and is very long if compared, for example, to the time needed to typically look down at HDD: in this case, in fact, few seconds of picture observation on HDD are enough to a skilled pilot to identify a target, while a mission in the SIRPH mode can reasonably last several minutes. Therefore this long mission time requires that the picture shall be as much comfortable as possible to prevent symptoms of ataxia to the pilot, or simply to prevent an excessive and intense workload. For this reason the acceptability of residual vibration level cannot be evaluated only on the basis of a loss of picture resolution or MTF.

With reference to Figure 1, if the aircraft structure has a very high level of stiffness (ideally without any static or dynamic deformation) the mechanical stresses due to the aircraft vibration are induced to the IR Sensor, HUD and Head Positioning Sensors without degradation. In reality the A/C structure does not obviously have infinite stiffness, and static and dynamic deformations have to be compensated with respect the A/C axis system, as it has been already mentioned in the previous sections. The helmet is mounted on a sort of 'shock absorber' with unknown characteristics. The helmet displays are solid with the pilot and they are not correlated with the IR sensor for vibrations; a stable picture to be displayed is therefore necessary and can be achieved by stabilising the IR picture. That provides the IR sensor LOS with a sort of inertial reference.

The SIRPH mode has to be designed taking into account also the following factors:

a. The human eye is generally able to detect the spatial flicker of the displayed picture with about 0.4-0.45 mrad vibration level, but the perception of the residual vibration is not necessarily disturbing. The spectrum of this residual vibration is a very important factor to be considered: in fact periodical vibrations-motions are generally more disturbing than vibrations which are random (typical in avionics application).

b. The stabilisation loop band has to be wide enough to cut down to acceptable levels the vibration aliasing. A high level of aliasing can really confuse the pilot, as it is visible in the form of travelling waves on the picture.

c. The limited resolution of the head tracker system implies that an angular noise is superimposed to the helmet angular position data. This noise could affect the design of the system: therefore the statistics of the angle data noise have to be clearly known.

6.2 Automatic hot spot detection

The use of the SIRPH mode in a combat scenario requires the implementation of an automatic capability to highlight targets, so that the mode is fully capable to cope with such mission. Visual identification of hot spots has the defect to be really effective only when the thermal signature significantly exceeds the background. Figure 6 shows the time needed to visually search a hot spot, within a typical SIRPH FOV of 25-45 degrees, as function of the hot spot visual contrast[4]. Visual detection in case of a 5% contrast target requires more than 6 times the time to detect a very high contrast target, or even more in the SIRPH as the specific attention of the pilot is dedicated to navigation.

If the IR sensor is provided with an automatic detection capability, hot spots can be usefully highlighted by superimposed synthetic high contrast markers which, however, do not hide the

picture of the hot spots, as the contrast level is a very important information when using IR devices.

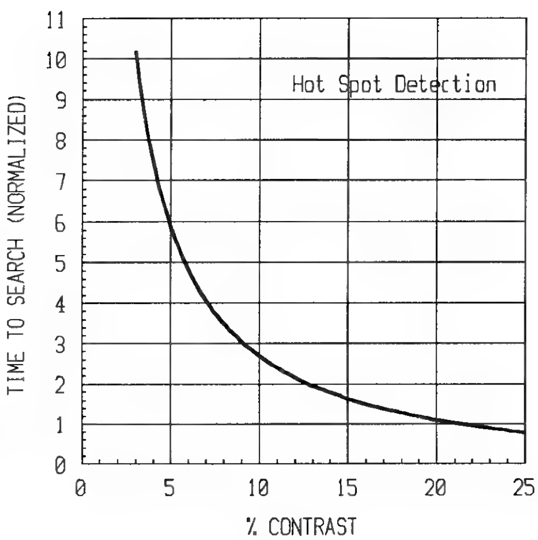

Figure 6. The time to visually detect a hot spot depends on its contrast. In this case a 5% contrast target is 6 times penalised with respect to a 20% contrast target.

6.3 Picture contrast control

When flying with SIRPH a picture with an IR contrast distribution is overlaid to the real image from the scene which, of course, has a visible light contrast. The two (i.e. IR picture - Visible image) have different characteristics, and these differences vary with weather, temperature and scene condition.
In presence of a perfect contrast controlled IR picture - shown in Figure 7 as the MTF curve named A, while B and C curves refer to bad contrast control cases - contrast and brightness of the HMD have to be constantly adjusted to maintain the same contrast for any variation of the ambient light even with the weak light of the night[5].

The scene seen by the IR sensor during SIRPH can change rapidly due to the pilot's head and A/C movements, and consequently the radiation level can change very rapidly, as the background or the objects within the IR scene might have very high temperature differences. Clear sky, for example, in high visibility conditions could be much colder than ground or sea. When the IR sensor LOS passes from a condition to another, the radiation content might considerably vary, while the relevant picture on the HMD should maintain the same average contrast and brightness level. Variations on the average equivalent contrast of the picture require adaptation of the pilot's eyes. Furthermore, continuous variation of the average equivalent contrast or too long adjustment time are significantly disturbing, and can cause partial loss in the perception of the scene.

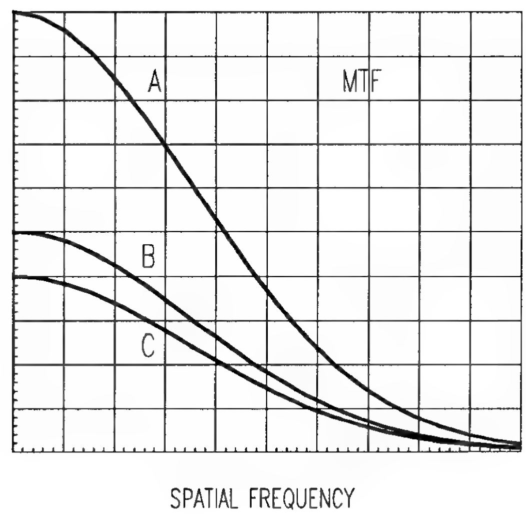

Figure 7. The IR picture MTF is strongly penalised by an insufficient brightness - contrast control of the HMD as the ambient light condition varies. The contrast A for a well set of the brightness can be decreased to B and C with an sufficient feedback on the ambient light.

Automatic Video and Scene level Control (VSC) is therefore necessary. The adjustments of the contrast level with reference to the scene changes should require no more than 2 - 3 video fields (40-60 ms), in accordance with the dynamic requirement seen in Section 5. The adjustment should be such not to penalise small contrasts with respect to high contrasts, especially in the central area of the HMD FOV, and to avoid a wrong exposure of the objects and obstacles in the scene. This latter function could be performed by non-linear processing of the picture, suitably fragmented. The HMD CRT gamma should be also corrected to match at the best the HMD characteristics .

7. IR TO LLTV PICTURE TRANSITION

The IR sensor coverage, due to physical/ mechanical limits and/or installation constraints, can never be equivalent to the full volume generally covered by the pilot's head in his own movements. Outside these limits the IR picture should be substituted - on the HMD - with pictures generated by other optronic sensors. The HMD is normally provided with LLTVs for night operation (i.e. the so-called Night Vision Enhancement); the LLTVs are aligned with the HMD LOS and are capable to provide the pilot with a light intensified picture, without any limitation to pilot's head LOS. Within the zone covered by the IR sensor the LLTV picture is obscured, off this zone the LLTV picture is displayed. Particular care must be given to the IR sensor/LLTV picture transition.

Upon the exceedence of IR sensor FOR, or when entering an obscured area (for example due to a non-optimal installation of the FLIR sensor, with consequent interference of the A/C structure with the FOR), the IR picture fades out and the LLTV picture fades in (see Figure 8), and vice versa. To avoid noisy transitions from and to LLTV pictures when the HMD LOS is approaching the transition limits (boundary line), an hysteresis should be included in the process. With reference to Figure 8 the IR image should be displayed on the HMD until the HMD LOS exceeds the IR sensor's FOR, and should be faded in as soon as it enters the line marked with H (hysteresis) loci.

To minimise the transition time as the HMD LOS enters the H Loci, the IR sensor's LOS should, even when it is faded out, continue the angle tracking until one of the input steering angle is within the IR sensor FOR limits, and should be frozen for off-steering angle. In this way the IR sensor should be capable to enter normal conditions within a shorter time if compared to the pilot's typical reaction time. The IR sensor should also provide the HMD with the indication of IR sensor FOR edge proximity to allow the HMD to fade the IR video signal and enable the LLTV signal.

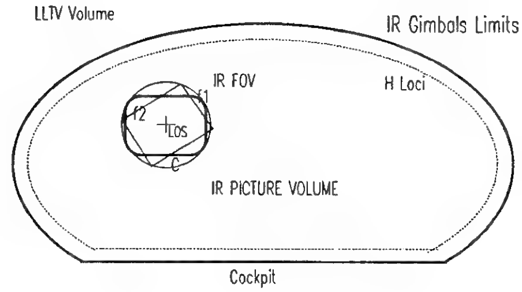

Figure 8. IR sensor FOR is limited by gimbals and/or installation constraints. Outside the FOR the IR picture is substituted by LLTV picture. The IR picture is obscured in the lower part to allow cockpit management. Figure 8 shows two possible orientations of the FOV within the circle centred on the LOS.

To increase the dynamic of such transition the IR sensor can provide the FOR edge proximity indication when the angle position and rate commands lead to a circular FOV (line C - circle - of Figure 8) circumscribing the SIRPH FOV (f1 and f2 lines in the example of Figure 8) to exceed the useful IR sensor FOR in approximately 200-300 ms. The IR sensor provides HMD with an indication of valid data when the circular FOV, as defined above, is fully within the FOR.

8. SAFETY ASPECT WHEN NAVIGATION IS SUPPORTED BY IR PICTURE

In order to allow a safety use of SIRPH when flying and landing, severe requirements in terms of reliability must be satisfied. A failure could, in fact, compromise mission success, aircraft survivability and, even, pilot's safety.

A failure which results with an increase of the overlay errors is extremely critical as, at night or in adverse weather conditions, this effect could be not evident to the pilot. In general, any failure which may cause a wrong but believable feedback of the A/C attitude is safety critical.

Many factors must be considered in the computation of the global reliability of the SIRPH mode: in addition to those of the IR sensor and HMD it is necessary not to forget those from the interface link, but the significant difference between the navigation by using the HUD - where any LOS (i.e. IR sensor , HUD) is fixed - and the navigation with SIRPH is that the IR sensor LOS is mechanically steered and slaved to follow the

pilot's LOS which is moving as well. The reliability contributions from the IR sensor motors, resolver, control loop, and from those of the head tracker, decrease the global reliability of SIRPH, thus determining under such aspect an unavoidable disadvantage with respect to the same use but with the HUD (see Figure 9).

An accurate design of an on-line and real time built-in-test is essential to detect any critical failure and to allow an immediate transition to other safer navigation modes.

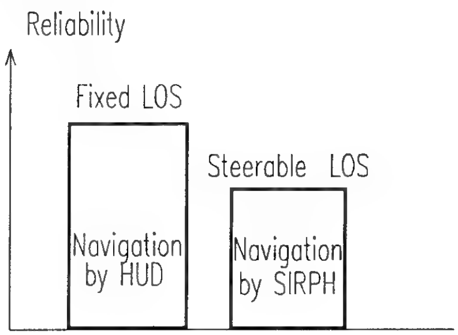

Figure 9. A navigation mode which uses the IR sensor and HUD offers higher reliability than that offered by SIRPH. IR sensor's motors, resolvers, control loop electronics, IR sensor/HMD digital link, head tracker, necessary to operate in the SIRPH mode, increase the fault probability.

9. PROPOSAL FOR IR AND LLTV PICTURES FUSION

Advanced HMD has normally available two different sensors capable to operate at night: these are two LLTVs integrated within the helmet shell itself and the IR sensor. The LLTVs have the same practical limitation in pointing as for the helmet, while the IR sensor has a defined FOR. Within the limits of the IR sensor FOR it is reasonable to think about the use of both sensors at the same time to increase the vision capability. The function is useful to overcome the problem of the 'IR cross over effect' (zero contrast condition) which is critical when flying nap of the earth (NOE) during twilight.

The fusion of LLTV image with IR image cannot be easily achieved by simply summing - with appropriate weights - the two images. The major problem related to the fusion is, in fact, the difference in contrast responses to the scenario characteristics detected by the two sensors. Targets or obstacles which present high luminance to LLTV sensors could emit a very low radiation in the typical IR waveband. Furthermore they could modify their own contrast depending on the atmospheric conditions and time. A simple mixing of the two pictures could therefore decrease the resulting signature of the objects instead of improving it.

The following rules should be considered while designing suitable image processors for IR/LLTV images fusion:

a. the evidence of the obstacle edges is the most important requirement for navigation. The dynamic grey scale has less importance.

b. high contrast enhancement, absence of blur, and good picture stability have to be achieved for visual recognition or identification of targets.

c. good uniformity of the picture background is important in the case of small target visual detection.

Specifically to improve the navigation capability, which is the task of the SIRPH mode, rule a) has to be applied.
A 2D filtering of the IR picture to enhance the edges of the obstacles could be implemented. The filter will enhance both white-to-black and black-to-white transitions, so to be independent from thermal contrast response. The filter should output a white level for the edges. This signal should be then summed up to the LLTV video signal, thus increasing the evidence of the obstacles.

The absolutely essential requirements for imaging navigation systems - i.e. the perfect overlay with the external world and the real time response (minimum delay from scenario to be gathered until picture presentation) - must be satisfied by a suitable design of such 2D filter.

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COVERT NIGHT/DAY OPERATIONS FOR ROTORCRAFT (CONDOR) PROGRAMME

T H Southam
CONDOR Project Manager
Man Machine Integration Department
Defence Research Agency, Farnborough
Hampshire, GU14 6TD, UK

ABSTRACT

CONDOR is a major joint US-UK project that will support a comprehensive demonstration of the functionality of current and future attack helicopters under day/night adverse weather conditions in a nap of the Earth environment. The aim of the programme is to investigate the integration of a suite of avionics, sensors and displays for battlefield helicopters and to assess their effectiveness during ingress, egress and attack phases of the mission. The concept features a precision navigation system which together with a steerable sensor coupled visually, via a helmet-position sensing system, to an advanced helmet mounted display with a wide FOV, full colour and laser eye protection enables a virtual outside world overlaid with appropriate flight and mission information to the pilot. The programme includes development and building of the advanced hardware, research into the human factors issues connected with their exploitation, symbology development coupled to a detailed application in a full mission scenario. Flight demonstrations are scheduled to take place in both the Lynx at DRA and with subsequent testing in the US to exploit a new full-authority FBW flight control system with mission configurable control laws.

1. INTRODUCTION

1.1 The CONDOR programme is a collaborative R&D project to develop an Advanced Visionics System (AVS) coupled with advanced flight control and precision navigation systems to demonstrate enhanced battlefield operations by day and night in a Degraded Visual Environment (DVE). The visionics system consists of a colour, wide Field Of View (FOV) helmet mounted display with laser eye protection and virtual cockpit display utilising miniature "Flat Panel" display technology. The flight control system will be digital fly by wire technology incorporating mission adaptive control laws. The precision navigation system will be integrated using GPS, INS and digital terrain data.

1.2 Originated from a proposal by GEC Avionics, at Rochester (UK), to the US Army to repackage fixed-wing equipment into a helicopter, in order to provide a flight demonstration of a night/poor weather capability for battlefield helicopters. US interest in the

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CONDOR demonstrator prompted an approach to the UK, in mid-1988, to collaborate in a joint programme under Nunn funding arrangements. The discussions and negotiations concerning CONDOR have identified the potential benefits of such a programme in expediting and enhancing the ongoing research into Visually-Coupled Systems (VCS) for helicopters. International co-operation has been formalized through the signing of a Memorandum of Understanding (MOU) with the United States, which defines a 48 month programme. The MOU was signed in 3 Dec 93 and will augment UK research and development of VCS. It provides for the US to develop, build and supply the CONDOR Advanced Visionics System (AVS), which will be a wide-field, full-colour VCS; in return, the UK will produce formats, develop an integrated three-dimensional positioning system, and demonstrate the AVS in flight trials representing covert battlefield missions. Additionally, a GEC monochrome 40 degree FOV helmet will be available for development work in anticipation of AVS. Although the present UK platform for testing and demonstrating the concepts is identified as the Lynx, part of the work involves collaboration with US programmes using the Blackhawk, and the research is ultimately leading toward applications in future battlefield aircraft.

1.3 The VCS demonstration will use a battlefield mission scenario based on UK requirements, and will be flown over Salisbury Plain Low Flying Area. Suitable Helmet Mounted Display (HMD) and Head Down Display (HDD) symbology sets will be developed through a Symbology Working Group (SWG), simulation and then flight evaluation. If there are parts of the demonstration mission that cannot be flown in a DVE, or requiring a virtual cockpit configuration, with no external view, then these will be performed in the simulators. CONDOR's generic helicopter VCS will develop ZD285 into a flyable test-vehicle to assess VCS hardware for defining the design specifications of future equipments. This will not demand advanced symbology nor advanced flight control enhancement. Furthermore, it will be a method of in-service support and minor development improvements in respect of off-the-shelf symbology for AH, thus finally leading towards the definition of symbology/VCS specification for an AH MLU. Simulation and flying within both tasks will aim to take this longer term objective of novel symbology concepts which may allow AH MLU to represent a major step forward in achieving the military objective of true day/night all weather operations.

2. OBJECTIVES OF UK CONDOR

2.1 The objectives of the CONDOR programme are to develop and demonstrate an advanced visionics concept coupled with an advanced flight control and precision navigation systems to improve the mission effectiveness of rotorcraft during day, night, and DVE conditions in a Nap-Of-the-Earth (NOE) environment. The specific goals of the project are to improve pilot Situational Awareness (SA) and to enhance vehicle control management. It will explore advanced technologies that will reduce the vulnerability and increase the

operational effectiveness of the battlefield helicopter.

3. COMPONENTS OF CONDOR

3.1 Under the Memorandum of Understanding (MOU) with the US, the United Kingdom is required to make certain specific contributions to the programme connected with AVS: an integrated navigation system, symbology for presentation on the HMD, the mission scenario, and the helicopter; and further to demonstrate them in the first flight demonstration. of the AVS. Because of this, and the information exchange taking place under TTCP HTP6, there has already been UK participation in trials conducted on the Crew Station Research and Development Facility (CSRDF) at NASA Ames. Two trials of direct relevance to CONDOR took place in early 1994: one concerned with available field of view in an HMD, the other with aspects of symbology stabilization. UK personnel participated fully in these trials.

3.2 There are several distinct areas of research, under ARP3D, which underpin the whole of the Technology Demonstrator Programme (TDP). The major activities are:

a. Development of Lynx ZD 285 into an integrated VCS research vehicle to assess VCS hardware and the definition of future equipment specifications.

b. Development and installation of an advanced integrated navigation system for NOE flight.

c. Development and implementation of suitable symbology sets for HMD and HDD.

d. Evaluation of Human Factors issues.

e. Development of a mission scenario for testing and identification of dependent variables for flight trial evaluation.

f. Flight trials using monochrome and then the colour AVS helmet.

4. PROGRAMME STRUCTURE

4.1 Clearly, the delineation between the short-term aims and the longer research objectives are not easily identifiable and therefore, for clarity, I have included both in the paper. The first has the role of coordinating the effort. Each of the others has responsibility for specific technical areas, some commonality has led to several joint reports as milestones within the whole programme.

4.2 VISUALLY COUPLED SYSTEMS

4.2.1 **VCS Programme Plan** Within the DRA helicopter VCS research has been conducted on several fronts; symbology development and its evaluation in the simulator facilities; hardware integration and flight trials. The prime goal is to the demonstration of an advanced VCS in flight in the Lynx during 1995. Whilst the longer term research goal is to lay the foundation for developments beyond that time. The component activities, whether inherited from previous research or arising as newly recognized requirements, must be

clearly defined and coordinated.

4.2.2 **Working Groups** The Symbology Working Group (SWG) has been established to develop agreed standard symbology sets for HMDs. It has promulgated a definition of the system to be used in the development, which will be Virtual Applications Prototyping System (VAPS) running on Silicon Graphics hardware. This common standard permits the direct exchange of data files and facilitates exchange of information with the Aeroflight Dynamics Directorate at NASA Ames, who is compiling ADS46, which will constitute the future US Army guidelines. It is an aim of the RWSWG to develop a set of formats that will potentially become the UK operational standard.

4.2.3 The requirement for simulation and flight trials provide ideal opportunities for the simultaneous study of issues connected with the use of the VCS. For example, using suitable CGI to simulate the outside world, combined with the further development of a predictive filter, may permit the manipulation of time delays, which constitute one of the most distinctive potential concerns in the use of these systems. Important questions however, continue to emerge and will require answers. The potential benefits of stereopsis and colour in an HMD, while seemingly obvious, have not been delineated in sufficient detail to ensure their optimum use. A question of this type, may potentially require separate experimental evaluation. Looking ahead to the next generation, and the benefits to be gained from upgraded specifications, such as total system latency, frequency response, increased visual field, or display resolution may only be approached using experimental apparatus. It is the present research that will identify the critical issues.

5 MISSION SIMULATION

5.1 **Objective** This assignment is directed towards a study of VCS technology as applied to battlefield helicopter operations: assessing its potential enhancement of effectiveness and defining its mode of application, particularly in terms of mission/task appropriate symbology. This will involve:

a. Establishing candidate display formats and VCS configurations, in association with the SWG.

b. Defining appropriate Measures Of Effectiveness (MOE) for trial evaluation of candidate systems.

c. Comparing the candidate systems, through mission simulator trials

d. Providing simulation support to flight trial activities.

5.2 This assignment is composed of several successive elements. The principal components are:

a. Display format implementation

b. Definition and implementation of VCS modelling and simulation requirements

c. Design of experiments

d. Mission simulator trials

e. Direct support of flight trials programme

5.2.1 **Display format** A major part of the effort within this assignment toward defining the formats for testing takes place within the SWG, in association with the other VCS assignments. The software required to generate symbology for presentation in the simulator will be prepared in accordance with guidelines that are evolving to ensure maximum portability between the facilities involved in the VCS assignments.

5.2.2 **Modelling and simulation requirements** Key aspects of the task addresses the configuration of the mission simulator at DRA Farnborough are:

a. The existing helicopter dynamics model has been upgraded to be compatible with the DRA Bedford simulation. Modifications, as indicated by simulation will be incorporated as required to maintain the compatibility.

b. A GEC helmet and an associated head position sensor have been installed in a generic Attack Helicopter front cockpit mounted on the Farnborough 3 degree-of-freedom motion platform. Motion will be used for maximum realism as well as commonality with the Bedford simulation.

c. The visual environment for the VCS simulation is provided using computer generated imagery derived from a high power image generator (Silicon Graphics Onyx Reality Engine). Latency in the visual system, a key factor, and substantial progress has been made in reducing it with the use of a newly-developed predictive filter. Future work will quantify and further reduce this parameter. It is envisaged that terrain representations developed for other applications are being used, together with a thermal imager simulation.

d. A threat environment for mission simulation is be generated using computer-controlled combatants currently under development for the HOVERS facility at Farnborough.

5.2.3 **Experimental Design** Each trial performed on the mission simulator will be based on a detailed experimental design. The initial experiment performed on the mission simulator is fully representative:

a. A series of short tasks was defined, each taking the form of a limited reconnaissance mission. Emphasis in the trial was on survivability and threat evasion, particular attention being given to placing realistic demands on the VCS. Thus, in the design of both the operational scenario and mission briefings, task elements which exercised the VCS in different ways were brought together.

b. The MOE for the trial were defined. These were related to the survivability of the aircraft as a

whole, for example, measuring response times and the duration of the existence of threat line-of-sight in addition to MOE adopted in previous trials.

c. Techniques for analysing the trial results were defined and appropriate software developed.

5.2.5 **Direct support to flight trials programme** It is anticipated that simulation trial results will influence the selection and integration of displays for the CONDOR flight trial programme. Furthermore, the flight tests will provide validation of the simulation activities. Following the initial simulation trials, the Farnborough mission simulation facility will be used to support the integration of the HMD on the Lynx in preparation for flight trials. It is anticipated that fine tuning of display parameters will be accomplished on the simulator prior to installation in the aircraft.

5.2.4 **Mission simulation trial** The task of performing the mission simulation trial consists of several elements:

a. Organizing subject aircrew from operational squadrons.

b. Preparation of a trial schedule and trial and mission briefing notes.

c. Trial execution.

d. Analysis of results.

e. Trial report.

6 INTEGRATION

6.1 The objective of the assignment is to install, integrate and provide a mission demonstration of an advanced VCS in the DRA Lynx ZD285.

6.2 The principal components of the assignment are:

a. Full system specification.

b. Detailed system design.

c. Installation of equipment and its integration with existing systems.

d. Developing software for information management and symbology generation.

e. Trialling and refining the system in stereotyped flight manoeuvres.

f. Scripting and flying an armed reconnaissance mission.

g. Data analysis and interpretation.

6.3 **Full system specification** The required data transport times and rates will be defined, and the VCS temporal and spatial parameters and error allowances determined. This will enable other assignments to direct their efforts in a practical way toward flight trials preparation and giving the Lynx the necessary degree of fidelity.

6.4 **Installation of equipment** Part of the essential equipment has already been acquired, and acquisition is underway. Current development activity is defining the limitations of present technology, and will point the way to future research appropriate to the longer term research goals. Central to the work is the design and installation of an upgraded VCS in the Lynx ZD285. The major equipment consists of:

a. **VCS Platform:** A high speed pan and tilt platform with a wide field of view IR sensor, which has already been installed on the nose of the helicopter.

b. **HPSS:** The HPSS is a GEC Avionics DC magnetic HPS installed in October 1993. The objective is to develop a system that will enable accurate overlay of flight symbology and the sensor image on the HMD, so that it is conformal, while allowing the aircrew the freedom of movement. The essential system features require an accuracy of 1 mR, minimum head-born weight on helmet with a large head motion box to provide a high angular and positional coverage.

c. **HMD:** The GEC Avionics 50 degree FOV helmet is already installed. The successful US-UK collaboration, under the MOU signed in Dec 93, enables the delivery of a CONDOR AVS helmet towards the end of 1995. This will then upgrade the Lynx system from monochrome to colour. The helmet, together with the VIPER graphics generator, will provide the interface to the existing systems and permit the second phase of the flight trials to begin.

d. **Symbol generator:** The current system will provide the symbol formats for the VCS trials leading up to the technical demonstration. The VIPER symbol generator will replace the existing system to provide the Lynx with an expandable, colour capable HMD/HDD. The new complex format generator will be sufficiently flexible to enable symbology and sensor images to be stabilized to a variety of references, allowing an iterative approach to a virtual cockpit environment. It is required to be Silicon Graphics compatible and easy to program. It is colour capable with an integral scan converter to provide high TV line rate to HMD. It also has Mil-Std-1553B data bus interface and capacity for future expansion.

e. **Bus controller:** Conforming to Mil-Std-1553b, and already installed, it will allow easy flexible modification of the message transaction tables.

f. **Inertial platform:** The Litton laser gyro IN platform, already installed, which will provide an accurate attitude reference system and will be

part of the integrated navigation system.

g. **Global Positioning System (GPS):** The Cossor GPS, already installed, will provide a small, lightweight and accurate navigation for VCS trials and will ultimately be integrated with the INS.

h. **Control and Display Unit (CDU):** The Litton CDU which is being procured to control the INS and GPS. Its spare processing capacity may be used in the integration of the INS and GPS.

6.5.1 A ground-based rig will be used to assist in electronic integration which will also permit the study of the various issues that may arise during the development, such as aspects of filtering and prediction in controlling the VCS. This effort will be aimed at reducing the effective lag of the VCS, which is currently estimated to be about 100 mS, a value that is of borderline acceptability.

6.6 **Software development** Current programming work is producing software that is suitable for use in flight by the flexible symbol generator interfaced with the Lynx's Flexibus. With the move toward standardization across the groups contributing to CONDOR, it is anticipated that this work will migrate to Silicon Graphics machines running the VAPS development package. When this facility has been linked with the ground-based rig, the CONDOR formats developed by the SWG will be examined and exercised prior to aircraft installation.

6.7 **Flight manoeuvres** Baseline data for the Lynx, without VCS, were established during trials in the winter of 1992/3, concentrating on flying task elements during daylight and at night. The phase 2 VCS trials, starting in November 1994, will characterize the change in performance due to the introduction of the VCS. The flying task elements will be assessed on a course marked out on the airfield. They have been designed to call on all aspects of the flight symbology, both on and off-boresight. Being based on the ADS33C, the performance measures should be quantifiable and it enables a precise data exchange with the US.

The ten elements are:

a. Hover recovery
b. Pirouette
c. Target turn
d. Slalom
e. Precision landing
f. Acceleration / deceleration including quick stop.
g. Vertical re-mask with lateral sidestep
h. NOE course (Long Valley route)
i. Confined area landing
j. Slope landing

Elements a to g will be assessed by performance measures, which are yet to be specified in detail. For h to j, formal questionnaires will be used.

6.8 **Armed Reconnaissance Mission Flight Trial** A mission scenario will be constructed from the agreed set of elements first defined by the SWG and refined as a result of the simulation trials. It will include NOE flight and reaction to suddenly-appearing threats,

as well as the use of the IR sensor. It is anticipated that large sections of mission will be identical with missions previously flown on the simulator, over the same terrain. In previous simulations this has been produced using ASP Department's model board, but in future will generally be based on computer-generated imagery. The mission trial will be the culminating flight activity that arises out of the preceding research and development on VCS in helicopters.

6.9 **Data Analysis and Interpretation** Data will include a video recording, automatic data collection from the Lynx systems, and pilot questionnaire responses. The analysis will be aimed particularly toward an assessment of the enhanced capability of the Lynx in this type of mission, the reduction in pilot workload, and the strengths and weaknesses of the particular VCS that is installed. Whether a monochrome GEC helmet system or the AVS is used, the results should define the appropriate exploitation of available VCSs, as well as the preferred refinements for the next generation of research VCSs.

7 CONTROL INTEGRATION

7.1 This assignment is concerned with the integration of helicopter HMDs with the aircraft controls and their response characteristics. An area of particular interest is the compensation for poor visual flight conditions through adaptive changes. This may involve the nature of the response evoked by control activity. However, in this context, it is the dynamics of display elements that is paramount. Nevertheless, display and response characteristics will require parallel changes in order to maintain compatibility, and they must be related to the task activity, whether high-level cruise or near-ground slow manoeuvre.

7.2 **Work breakdown** The principal components of the programme are:

a. Display format implementation

b. Integration of the VCS with the Bedford Advanced Flight Simulator (AFS)

c. Design of experiments

d. AFS trials

e. Direct support of flight trials programme

7.2.1 **Display format implementation** The formats tested in the AFS will be those developed by the SWG. It will then be provided to Farnborough, to form the basis of the symbology software used in the mission simulation. As the CONDOR programme proceeds, format sets relevant to forward flight and transition will be handled in a fashion similar to that already shown in the test of hover/low speed. Other format types, such as systems or tactical symbology sets, will be considered in so far as they affect the pilot's handling of the aircraft.

7.2.2 **Integration of the VCS with the Bedford AFS** A GEC HMD has been brought to Bedford and integrated with a DC magnetic head tracker to form a VCS within the AFS. This HMD has a 53 field of view, and is identical in all important respects with the HMD used in the Farnborough mission simulator. An important continuing activity is directed at reducing the effect of latency in the system, partly through reconfiguration of the hardware and partly, through the development of software predictive filters.

7.2.3 **Design of experiments** The simulation trials on the AFS will concentrate on simple stylized manoeuvres, such as precision hover, and the effect of different dynamic conditions for the various display elements, such as quickening of the sideslip indicator or velocity vector, will be assessed using a combination of direct instrumentation readouts from the AFS and the responses provided on subjective questionnaires. A second simulation trial, planned for early 1994, will address issues to be identified by the Lynx trials team that are relevant to the forward flight formats required for demonstrating the fully integrated VCS.

7.2.5 **Direct support of flight trials programme** Clearly, simulation results will influence the selection and integration of displays for the CONDOR flight trial programme. Furthermore, the flight tests will provide validation of the simulation activities. It is anticipated that some fine tuning of display parameters may be appropriately addressed on the AFS, especially those that may be sensitively affected by acceleration.

8 NAVIGATION SYSTEM

8.1 **Objective** This assignment will provide the necessary research for the development and integration of a precision positioning system for CONDOR. The assignment will draw extensively from the work performed in the navigation assignment which is investigating techniques for optimally fusing and integrating data from disparate sources such as INS, TRN,
GPS, air data etc. A fundamental requirement for the CONDOR system is to display map derived data within the helmet display system and to provide an accurate height channel. This dictates the development of a positioning system generating position information relative to a map database, hence the need for a terrain referenced system offering both good height and map referenced position data.

8.2 **Work breakdown** The work follows a structured plan to meet the objectives of CONDOR through the following distinct phases:

a System Specification

b INS/GPS integration and trials

c INS/GPS/TRN integration and trials

d Full system integration with other available sensors

e System demonstration

8.2.1 **System Specification** The precise requirements dictated by the VCS, in terms of data quantities, data rates, acceptable data latencies will to some extent dictate the architecture of the system. The design philosophy of the system is heavily based on a reconfigurable architecture providing the potential capability for various navigation sensor integration options.

8.2.2 **INS/GPS Integration and Trials** A loosely coupled GPS/INS system has been flown in Sea King in late 93/early 94; it will be made available in Lynx later in 94.

8.2.3 **INS/GPS/TRN Integration** The integration of TRN into INS/GPS will be a two phase approach. The Integration Computer will be used to host the map data base and the TRN algorithms. Phase 1 will simply use TRN height information, being of better quality than GPS height and feed the information into the GPS/INS solution, thereby greatly enhancing the overall height solution. Phase 2 will if necessary perform a full INS/GPS/TRN PVT integration within the integration computer or adopt a closely coupled scheme if security restrictions will permit the export of pseudo range and range rates from the GPS receiver.

8.2.4 **Full system integration with other sensors** It is expected that other sensors will offer additional information, such as Air data and Doppler information. These will be integrated with the INS/GPS/TRN solution as is deemed appropriate and as the sensor data becomes available.

8.2.5 **System Demonstration** Following the trial of a INS/GPS based positioning system on Sea King in Dec 93, it is planned to demonstrate it in the Lynx in Oct 94. A system based on INS/GPS/TRN integration will be demonstrated in Lynx in Dec 95.

9 MMI ISSUES

9.1 VCSs represent a developing technology, and all current versions have limitations arising either from the targeting of specialized applications; from financial constraints lowering the specification or from the immaturity in the design of components and systems. The factors that have limited the exploitation of VCS technology have been hardware-based. Advances in all the relevant technologies, however, are rapidly improving the achievable specification of VCSs. There is therefore an need to perform research that seeks to define the best balance of characteristics of future systems, and to identify the best way to exploit new capabilities that can be introduced into them. The chosen approach has been to obtain components with the highest available specification, with the intention of an in-house integration. Refinement of the overall system specification

requires consideration of the MMI, especially the aspect that is unique to VCS: the transfer function, including its time derivatives. In a helicopter application, the perturbation of this function by vibration is an additional issue.

9.2 There are several avenues to follow in testing aspects of equipment that does not yet exist.

a. Bench-top experimentation

b. Controlled degradation of natural senses

c. Ground-based simulation

d. Testing of research equipment with some of the relevant characteristics

9.2.1 **Bench-top experimentation** Associated with the CONDOR TDP, there are plans for exploiting MMI's experimental displays for investigating the possible utilization of stereopsis and colour as an additional cue for decluttering displays, for studying the potency of different depth cues in displays, and for determining the best way of using a colour overlay to enhance the effectiveness of sensor images. These displays can also be used to explore the effects of display technologies such as antialiasing.

9.2.2 **Degradation of natural senses** During research, using equipment that more than meets the requirements for a particular task, it is generally possible to examine the minimal requirements by controlled degradation of its performance. If no equipment yet exists that meets the minimal requirements, however, this approach is not available. As an example, the question of the appropriate field of view of an HMD will be explored in flight trials in which the pilot's view is selectively narrowed using a partial occluder. This will follow on from simulator trials on the same question performed early in 1994 an NASA Ames. Another area in which this approach might be exploited is in the use of a head-mounted device incorporating a head-mounted camera, with controlled delays introduced by an accessory system, possibly based on frame stores. Such an approach would bypass the current limitation that small delays can only be investigated using prediction, which is intrinsically uncertain.

9.2.3 **Ground-based simulation** MMI Department will shortly take delivery of the Advanced Panoramic Helmet Integrated Demonstrator System (APHIDS), which will present computer-generated imagery on a wide field of view, colour HMD. There are plans for studying a wide variety of human factors issues, under a fully-funded strategic research programme.

9.2.4 **Testing of research equipment** Under the MOU, the DRA will gain access to the AVS, the Advanced Visionics System. This device cannot be considered a prototype for an operational system because the ancillary equipment imposes a serious weight penalty on the aircraft. Nevertheless, it will provide the opportunity for testing in flight conditions the effects of monocular vs binocular

symbol presentation, variable overlap, the uses of colour and stereopsis.

9.2.5 **HPSS** In companies with an established history of building VCSs, it is taken for granted that the raw signal from an HPSS is not good enough: it must be processed to give predictions so that the overall system response can be made adequately fast. This requirement arises not only from the update rate of the HPSS itself, but also from the latency imposed by other downstream components. In CONDOR, there are two dissimilar image sources that need to be controlled: one is the sensor, the other the symbol generator. They contrast strongly in processing time, inertia, and response to vibration. More important is the question of the required accuracy of the positioning, and the issue of whether an accurate velocity matching or accurate position matching is more critical, bearing in mind the likelihood of motion sickness. It is anticipated that the simulation at both Farnborough and at Bedford will use the existing VCS, upgraded with some form of predictive algorithm.

9.2.6 Both simulator facilities use computer-generated imagery as well as modelboards with cameras. It is probable that the issues of sensory mismatch will arise more prominently in the work on the AFS, because of its greater control over acceleration and the ability of that simulator to address the symbology dynamics to a greater degree of accuracy, whilst the issues concerning the usability of the images, over an extended period in a mission environment, will be addressed by Farnborough. The simulator facilities may prove too limiting to provide definitive answers on the required precision required for the VCS transfer function. In particular, the equipment will not match the performance, nor a realistic vibration condition, as for the advanced system installed in the Lynx. Refinement of the specification may depend on studies using the DRA vibration facilities.

10 HMD AND HDD SYMBOLOGY

10.1 Monocular HMDs have been in service in the US Army AH-64 for several years however, difficulties have been experienced in providing adequate SA and being able to reduce spatial disorientation and information conflict. The next generation of Commanche HMDs will use a different set of formats on a partially overlapping binocular display. In the UK, the Phase 1 Lynx flight trials will use a HMD format developed from the AH64A. This will prove most adequate to enable the shake-down of the integrated system. The format chosen for the initial demonstration is a result of work on the DRA simulator in conjunction with test pilots.

10.2 HMD symbology has a unique requirement for stabilization in various frames of reference; more generally, the symbol dynamics must be linked to flying qualities of the helicopter, the characteristics of the pilots' controls, and the movement of the pilot himself. CONDOR's demand for operation in conditions of a Degraded Visual Environment (DVE) imposes stringent requirements for the accuracy and intuitiveness of the symbology

dynamics. Definition and refinement of the drive laws is the aim of simulation now starting on DRA Bedford's Advanced Flight Simulator. Mission related tasks and manoeuvres, will be incorporated in simulation at DRA Farnborough concerned with the information requirements for the final demonstration. These trials will also consider the information distribution between HUD and HDD.

10.3 A symbology steering group has been established to maintain consistency of the symbology ideas exploited in the separate lines of research and development leading to CONDOR. This group will consider formats previously developed in the UK and in the US and available through TTCP HTP6, taking into account ongoing research activity, in order to arrive at a coherent and consistent format set. In the short-term, the development of ZD 285 into a flying VCS test vehicle will not demand advanced symbology of advanced control enhancement. In the longer term however, the necessary expertise exists to move more intuitively towards a more novel symbology set without the process of evolution from existing solutions such as AH64. In fact the aim of the whole process is to look forward towards an AH MLU. We must seek to provide unique novel symbology solutions that replace the external cues to attitude and groundspeed which a pilot naturally uses during low speed manoeuvring.

11 TRIALS AND EVALUSTIONS

11.1 **Data Recording and Retrieval** To obtain the maximum benefit from the envisaged CONDOR flight trials, a specialised comprehensive data recording system will be installed in Lynx ZD285. The airborne recording will utilise the 1553 data bus recorder, Heim data bus adapter and SVHS Video Cassette Recorders.

11.2 **Data Reduction and Analysis** Although it is not yet possible to define the analysis requirement of the UK CONDOR programme, the data from each flight test and simulation phase will be analysed and reported prior to proceeding to the next phase. This will almost certainly involve specialised expertise and/or equipment. Note that the criteria for assessing the flight trials evolve. They will be based on the overall aim of the programme: hence, some form of assessment of the adequacy of low-level piloting in a DVE.

11.3 The proposed flight test programme is divided into 4 phases and the outline objectives for each of the phases have not yet been clearly defined. However, it is anticipated that it will be necessary to refine these objectives as the programme progresses. Considerable research has already been done, and is continuing, under the auspices of the US/UK exchange programme TTCP HTP-6 at DRA(F) and NASA Ames and in UK industry under MOD-funded programmes, to develop display formats suitable for HMDs in helicopters. The development of VCS symbology will be an iterative process involving the complementary use of all of the DRA simulator facilities to maximize confidence in a particular symbology set, in a cost effective manner.

Subsequent trials phases will successively build towards a complete, VCS system to demonstrate the feasibility of flying NOE at night and in a DVE.

11.4 The following outlines the programme proposed. It is impossible to be precise about the number of flying hours required for each phase since the detailed objectives for the later phases will need to be refined in the light of experience gained from earlier phases.

12 CONCLUSION

12.1 The CONDOR programme of research provides the central thrust for developing an understanding of the capabilities and requirements of visually coupled systems. It gains considerable strength from its intrinsic association with the UK-US MOU and draws on additional input through TTCP HTP6 and other assignments. It will provide a solid foundation for future research that will inevitably surround this key technology. Monocular HMDs have been in service in the US Army AH-64 for several years however, difficulties have been experienced in providing adequate SA and being able to reduce spatial disorientation and information conflict. The next generation of Commanche HMDs will hope to overcome some of these difficulties. In the UK, the Phase 1 Lynx flight trials will use a HMD format developed from the AH64A. This will prove most adequate to enable the shake-down of the integrated system.

12.2 HMD symbology has a unique requirement for stabilization in various frames of reference. The symbol dynamics must be linked to flying qualities of the helicopter, the characteristics of the pilots' controls, and the movement of the pilot himself. CONDOR's demand for operation in conditions of a Degraded Visual Environment (DVE) imposes stringent requirements for the accuracy and intuitiveness of the symbology dynamics. Definition and refinement of the drive laws is the aim of simulation now starting on DRA Bedford's AFS. Mission related tasks and manoeuvres, will be incorporated in simulation at DRA Farnborough concerned with the information requirements for the final demonstration. These trials will also consider the information distribution between HUD and HDD.

12.3 A symbology steering group has been established to maintain consistency of the symbology ideas exploited in the separate lines of research and development leading to CONDOR. This group will consider formats previously developed in the UK and in the US and available through TTCP HTP6, taking into account ongoing research activity, in order to arrive at a coherent and consistent format set. In the short-term, the development of ZD 285 into a flying VCS test vehicle will not demand advanced symbology of advanced control enhancement. In the longer term however, the necessary expertise exists to move more intuitively towards a more adventurous symbology set without the process of evolution from existing solutions such as AH64. In fact the aim of the whole process is to look forward towards an AH MLU. We must seek to

provide the unique novel symbology solutions that replace the external cues to attitude and groundspeed which a pilot naturally uses during low speed manoeuvring. If this is achieved, we will have put in place, under CONDOR, the necessary research to enable the military objective to improve the 24 hour operability and effectiveness of helicopters at night and in bad weather.

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14. Abstract

Tactical rotary wing aircraft and low-level, fixed wing aircraft operating in high threat areas require improvements in night and adverse weather conditions in order to increase survivability, improve operational performance, and to reduce pilot workload. Recent developments and the results of on-going programs suggest that increased automation and optimized integration of sensors, guidance/navigation, control and display systems, and weapons provide approaches to greatly enhanced capability in night operation. Operations/missions of concern include fire-support, attack, reconnaissance, and special operations.

Automated positioning, precision tracking, communications and mission planning, and data entry will also be available. Recent developments in integration of multi-spectral sensors, smart weapons, architectures, and processor and data distribution systems will permit different approaches to core structures.

The purpose of the symposium is to support the evolutions and envelopment of alternative core structures which will lead to the fielding of effective low-level and N.O.E. night operations systems for fixed and rotary wing aircraft.

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